



**THREE-D
GEOCONSULTANTS
LIMITED**

Open File Report 88-14

**A STUDY OF THE POTENTIAL OF SPECIALTY
METALS IN NEW BRUNSWICK**

by

**Three-D GeoConsultants Limited
Fredericton, N.B.**



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New Brunswick
Mineral
Development
Agreement**

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Nouveau-Brunswick
L'Exploitation
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Hon. Morris Green, Minister

1988

A STUDY OF THE POTENTIAL OF
SPECIALTY METALS IN NEW BRUNSWICK

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REPORT 8815-1

prepared for: Mineral Development Branch
Mineral Resource Division
New Brunswick Department
of Natural Resources
Fredericton, N.B.

prepared by: Three-D GeoConsultants Ltd.
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March 31, 1988



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13 May 1988

New Brunswick Department of Natural Resources
Mineral Development Branch
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Fredericton, N.B.
E3B 5H1

Attention: R. Harris
Project Engineer

Dear Mr. Harris:

Re: Study of the Potential of Specialty Metals in New Brunswick:
Report 8815-1

We are pleased to submit the final edited report of the Specialty Metals Study.

Critical comments received from yourself and Mr. D. Thibault and those of Mr. L. Fyffe and Mr. R. Wilson, of the Geological Surveys Branch, have been incorporated into this edition.

I trust you will find the contents of the report to your satisfaction.

Yours truly,

THREE-D GEOCONSULTANTS LIMITED

David Keys

for F. Dwight Ball
Senior Geologist

FDB:bc

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1.0 Executive Summary

An extensive literature review has been undertaken for several specialty metals including beryllium, gallium, germanium, the rare earth elements plus yttrium, titanium, and zirconium. The objective of the study was to determine whether the geological environments in New Brunswick have the potential to host economic quantities of these metals. Established ore bodies around the world were evaluated and information on typical minerals, type of host rock, grade of the deposit and associated data was compiled. World production statistics, markets, price, saleable forms, processing technology, and uses of each metal are also presented. Alternative products and strategic resource considerations are discussed in the context of the development of a potential new source of supply.

The geological models suggested by these known ore bodies are compared with reported occurrences of each metal in New Brunswick. The models were also evaluated relative to the geological environments which exist in the Province. These comparisons permitted identification of those areas or rock units which have the potential to host mineral deposits similar to the known ore bodies. These favourable areas and/or rock units are discussed individually for each metal and recommendations for further evaluation of the potential are presented.

A summary of the locations/rock units with greatest potential is presented in the table below. A ranking has been assigned to each entry in the table as a method of indicating priority. The priority rating, and the recommended exploration approaches, are based on the analysis of the data presented in the report and are subjective. A perception of reasonable potential is implied but, as with most mineral exploration, an assurance of successful identification of an economically viable deposit is not suggested.

<u>priority</u>	<u>metal</u>	<u>mineralogy</u>	<u>geologic environment</u> <u>/rock type</u>	<u>location/lat.:long.</u>
1	titanium	anatase	paleoplacer	Taylor Village 45° 55' : 64° 35'
2a	beryllium	undetermined	non-pegmatitic Be	Burnthill-Dungarvon 46° 40' : 64° 45'
2b	beryllium	undetermined	non-pegmatitic Be	Juniper 46° 40' : 67° 10'
3a	REE	apatite	basic intrusives	Benjamin River 47° 55' : 66° 12'
3b	REE	apatite	basic intrusives	north-central N.B. 46° 00' - 48° 05' : 66° 00' - 67° 30'
4	gallium/ germanium	undetermined	oxidized Cu-Fe sulphide deposits (gossans)	north-central N.B. 47° 00' - 48° 00' : 65° 40' - 67° 00'
5	REE titanium zirconium	monazite ilmenite/ rutile zircon other heavy minerals	paleoplacer	central & eastern N.B. 45° 30' - 48° 00' : 64° 00' - 67° 00'

In addition to the locations/rock types listed in the table, the report outlines several other possibilities of lesser priority. These include investigation of the authenticity, geology, and mineralogy of several beryllium and rare earth element occurrences. Assessment of the occurrence of gallium and germanium in association with sphalerite in the Windsor Group in south-central New Brunswick, and in coal, oil shale, and the ash of these, is also recommended.

The report includes a map showing the locations of known occurrences and/or favourable geological units of these specialty metals in New Brunswick. An extensive bibliography and a glossary of terms are also included.

2.0 Introduction

2.1 Background

Recent technological advances have indicated that the demand for a group of metals, commonly termed the specialty metals, will increase in the foreseeable future. These metals have been labelled "high-growth" by international marketing specialists such as Kline and Company. The metals included in this group are beryllium, gallium, germanium, titanium, the rare earth elements and yttrium and zirconium.

The rare earth elements can be cited as an example of the coming demand for these specialty metals. Recent advances have indicated that researchers are moving very rapidly towards the development of economically viable alloys of rare earths which will be able to conduct electricity with almost no power loss due to conductor resistance. These "super conductors" have applications ranging from superfast computers to much less costly transmission of electricity. The impact of these developments on our society could very well outstrip that of the invention of the transistor.

Recognition of the developing demand for specialty metals has prompted a number of organizations, both public and private, to examine the role they will play in these developments. Several private sector organizations have initiated exploration programs aimed at the eventual production of specialty metals. The role to be played by the various public sector organizations involved, such as the New Brunswick Department of Natural Resources, depends upon their level of preparedness and knowledge of the potential for exploration and possible production of these specialty metals within their jurisdiction.

The New Brunswick Department of Natural Resources

has recognized the potential for the province in the developing demand for specialty metals. The Department also recognizes that to date little or no local interest in these metals has resulted in a lack of information relevant to their potential occurrence in the province. As well, the Department has a continuing mandate to encourage private sector exploration through the provision of relevant geological data. As a result, this study of the potential of specialty metals in New Brunswick was commissioned. This study will provide the foundation of basic information required for the province to prepare itself for the coming market demand in these metals.

2.2 Objective

The objective of this study was to determine whether the geology of New Brunswick has the potential for hosting economic quantities of beryllium, gallium, germanium, rare earth elements plus yttrium, titanium and zirconium.

2.3 Scope

The study was completed by:

- (a) determining, through a literature review, the typical host rocks/minerals of beryllium, gallium, germanium, rare earth elements plus yttrium, titanium and zirconium and the geological makeup (mineralogy and grades) of established ore bodies of these metals around the world; and
- (b) relating the geology of known ore bodies to that of New Brunswick in order to gauge the likelihood of these metals being present in significant quantities in New Brunswick; and

- (c) identifying possible areas of exploration in New Brunswick.

2.4 Methodology

2.4.1 Literature Review

2.4.1.1 Established Orebodies

A comprehensive search of the literature for sources of information pertaining to the geochemistry, mineralogy, geology and grade of established worldwide specialty metal orebodies was completed. In addition, sources of information pertaining to the processing technology, form of the saleable products and product price were accessed. The information assembled in this report thus comprises a catalogue of the known worldwide deposits of specialty metals. The data contained in the catalogue have been used as a basis to evaluate the potential of New Brunswick for hosting economic quantities of the specialty metals.

Production statistics published by the United States Department of the Interior's Bureau of Mines were used to establish a source list, by country, of world production of the specialty metals. Subsequently, a keyword search of the Phoenix System and the Georef data base at the University of New Brunswick yielded sources of relevant data. Geological details of the specialty metal producing orebodies worldwide were extracted from these data sources. In several cases the geology of depleted or closed orebodies, and of deposits currently in development was acquired, since the mode of their occurrence and emplacement was considered relevant to this study. The details of the geochemical behaviour of the specialty metals were gleaned in large part from the Handbook of Geochemistry published by

Springer-Verlag. During the course of extracting data from the various sources, information detailing processing technology and product form and price was identified and acquired.

A complete bibliography of the sources of information and data used in the preparation of the deposit catalogues is included in this report (Section 10.0).

2.4.1.2 New Brunswick Geology

Data specific to the potential of the specialty metals in New Brunswick is lacking. General geological information, however, is readily available through the New Brunswick Department of Natural Resources. The latter is available in two forms: 1) bedrock mapping and geological interpretation undertaken by the Department, published in several formats, and 2) reports filed with the Department by private sector mineralogical exploration firms for assessment credit on mining exploration claims.

Initially, the location and geological parameters of the known occurrences of specialty metals were extracted from the available information. The occurrences can be grouped in two classes: mineralogical and geochemical. Mineralogical occurrences are those at which specialty metal-bearing minerals have been identified. Geochemical occurrences are those at which specialty metals have been identified as being present through chemical analyses of rock, soil samples or stream sediment samples. An effort was made to include geochemical occurrences only of anomalous proportions. The determination of anomalous values was based on comparisons with apparent background levels within a given geographic/geologic area.

Geological information acquired, assembled and synthesized by the Department of Natural Resources is available

in several types of reports and maps. In addition to reviewing those data which were relevant to this study, personal contact was made with several of the Departmental geologists who have been actively involved in the generation of the provincial geological data base over the past decade and a half.

2.4.2 Data Synthesis

Subsequent to the identification of the specialty metal occurrences, the assembled geological data base for the province, with specific emphasis on the geology of the identified occurrences, was reviewed in order to provide a comparison with the geology of the worldwide specialty metal orebodies. This comparison was used to identify those areas in the province which held the most potential for hosting deposits of the specialty metals. Recommendations which could form the basis of further exploration and resource delineation within the province were formulated, and are presented.

3.0 Beryllium

3.1 Properties

Beryllium has an atomic number of 4, atomic weight of 9.01, specific gravity of 1.846 and a melting point of 1290°C. Beryllium, being the seventh lightest known metal, has physical and chemical properties that make it useful for various applications in both its oxide and metallic forms. The metal has great stiffness, exceeding that of other metals (including steels), useful heat dissipation properties, a very high strength-to-weight ratio, useful nuclear moderating and reflecting properties and good corrosion resistance. Beryllium oxide (beryllia) has similar properties that provide good heat resistance and electrical insulating properties, transmission of microwave radiation, great hardness, light weight and good thermal conductivity.

3.2 Saleable Forms and Price

The American Metal Market quotes 1985 prices for beryllium in eight forms.

1) vacuum cast ingot, 97% pure	\$US225/lb.
2) metal powder, in 5,000 lb. lots 97% pure	\$US196/lb.
3) beryllium-copper master alloy	\$US144/lb. contained Be
4) beryllium-copper casting alloy	\$US5.10-5.70/lb.
5) beryllium-copper in rod, bar, wire	\$US8.05/lb.
6) beryllium-copper in strip	\$US7.25/lb.
7) beryllium-aluminum alloy, in 100,000 lb. lots	\$US236/lb.
8) beryllium-oxide powder	\$US55.70/lb.

3.3 Production Statistics

	1981	1982	1983	1984	1985
	(tonnes)				
Argentina:					
-beryl conc.					
gross wt.	7	6	24	25	15
BeO content	1	1	2	3	1
Brazil:					
-beryl conc., gross wt.	853	1,135	943	1,407	1,500
Madagascar:					
-beryl in qtz., conc., industrial, ornamental	50	68	<0.5	46	50
Mozambique:					
-beryl conc., gross wt.	7	8	6	6	6
Portugal:					
-beryl conc., gross wt.	18	12	3	10	10
Rwanda:					
-beryl conc., gross wt.	59	69	32	44	27
South Africa:					
-beryl conc. (11%-12% BeO)	122	58	21	1	5
U.S.A.:					
ore (bertrandite)	n/a	n/a	n/a	n/a	8,636
metal	n/a	n/a	n/a	n/a	171
U.S.S.R.:					
-beryl, cobbled, 10-20% BeO	1,800	1,850	1,900	1,900	1,900
Zimbabwe:					
-beryl conc., gross wt.	42	52	47	19	38

n/a - not available

3.4 Uses

3.4.1 Applications

Beryllium has numerous and diversified uses ranging from miniaturized spring elements in electronic switching gear to brake shoes and heat shields in aerospace applications.

The metal's value results from the need for materials which possess a combination of high electrical and thermal conductivity and high mechanical strength along with good resistance to fatigue, stress relaxation, wear and corrosion. The miniaturization of electronic components is only possible with the use of a good thermal conducting material, which can dissipate heat quickly and is also a good electrical insulator. Beryllia ceramics fulfill both these requirements.

The remainder of demand in both the alloy and metal form was for the manufacture of molds for plastics dies; high-strength, non-sparking tools, springs, tubes and diaphragms for a wide range of measuring instruments; various beryllium compounds, targets for neutron activation analysis equipment, and radiation windows.

3.4.2 Alternatives

The literature reviewed suggested no alternatives to beryllium on the basis of performance. Composites of boron or graphite fibers are the most likely competitive material for structural beryllium. Phosphor bronze can possibly substitute for beryllium-copper alloys, although its inferior conductivity, fatigue and formability characteristics has limited its use. Sintered alumina can substitute for beryllia in ceramics where thermal conductivity is not a main consideration.

3.5 World Deposits

3.5.1 Beryllium Geochemistry and Mineralogy

Approximately 50 species of beryllium minerals have been reported. Over half are silicates, and the bulk of the

remainder are phosphates and borates. Beryllium is produced commercially from two minerals, beryl, $\text{Al}_2\text{Be}_3\text{Si}_6\text{O}_{18}$ and bertrandite, $\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$. Other relatively abundant beryllium minerals include chrysoberyl, Al_2BeO_4 , euclase, $\text{Be}_2\text{Al}_2(\text{SiO}_4)_2(\text{OH})_2$, gadolinite, $\text{Fe}_{1/2}\text{YBeSiO}_4\text{O}$ and phenacite, Be_2SiO_4 .

Beryllium is widely distributed in low concentrations in rock-forming minerals; it replaces silicon to some extent. These associations, however, do not provide opportunities for economic exploitation.

Beryllium, being a typical element of residual magmas, is correlated with such elements as lithium, boron and fluorine in rocks derived from late stages of the magmatic process. In albitized granites, muscovite granites, pegmatites (Section 12.0), skarn rocks (Section 12.0) and other metasomatically (Section 12.0) altered rock types, beryllium and fluorine are closely correlated. Fluorine compounds play a role in beryllium transport.

3.5.2 Deposit Classification

Classification of beryllium deposits commonly rests on their being either pegmatitic or nonpegmatitic. The latter include pneumatolytic-hydrothermal (Section 12.0) and disseminated replacement deposits. The distinctions, however, between the types are not always clear or rigidly applicable since they are gradational in character.

Most of the known beryllium occurrences of the world are in granite pegmatites distributed in Precambrian Shield areas and some belts of younger crystalline rocks. The nonpegmatitic occurrences are mainly in the younger orogenic belts, characterized by large granitic intrusions. The close spatial relationship

of beryllium deposits, both pegmatitic and nonpegmatitic, to granitoid bodies is widely recognized.

3.5.2.1 Pegmatitic Deposits

Pegmatites were at one time a major source of beryllium production. Beryl was and is the most important mineral of pegmatitic beryllium deposits, although some past production was based on chrysoberyl.

Felsic pegmatites fall into two mineralogical classes:

- 1) Simple pegmatites consisting of quartz, alkali feldspars and minor micas; rare minerals are either absent or present as accessories only.
- 2) Complex pegmatites containing, in addition to quartz, feldspars and micas, rare minerals in considerable abundance and variety, including beryl. Individual crystals of some of these may be of immense size.

Pegmatites of the first class occupy dykes, veins or flat lenses at or near the margins of granitoid intrusions, or as constituents of regionally developed migmatite complexes. Complex pegmatites may also be associated with granitic intrusions, particularly in their marginal zones. Those connected with intrusions of syenite and nepheline syenite are likely to be particularly rich in "rare" minerals. The complex condition is apparently determined by factors of regional significance, for within one granite-granodiorite province pegmatites will be uniformly simple, while throughout another (e.g. the Appalachian province of North America) complex mineral assemblages will be the general rule.

B & B Minerals Company Incorporated, in 1984, recovered approximately 9 tonnes of beryl during mica mining in pegmatite at Cochran, Georgia. The beryl was shipped to the Brush Wellman plant near Delta, Utah for processing into beryllium oxide. Pacer Corporation recovered a small tonnage of hand-cobbed beryl, along with feldspar and mica, at its pegmatite operations in 1984. The firm operated several leased mines in the Custer County area of South Dakota and also purchased beryl from independent miners in the area. The beryl was shipped to the Brush Wellman plant near Delta, Utah for processing into beryllium oxide.

The literature suggests that outside the United States, the balance of the world's beryllium production is derived from pegmatite-based beryl mining. Only the U.S.S.R. and probably China, outside the U.S., are producers of beryllium metal.

3.5.2.2 Nonpegmatitic - pneumatolytic hydrothermal deposits

This group of deposits and/or occurrences includes disseminations of beryllium minerals in granite, greisens (Section 12.0), quartz veins, plagioclase-quartz veins and skarns. They are formed under temperature conditions somewhat lower than those of pegmatitic deposits but higher than those of common metallic vein deposits. They are typically found in areas in which pegmatites are not well developed, suggesting that they form under conditions precluding the development of pegmatites. The plutonic bodies to which these deposits are related are commonly bi-micaceous granite, muscovite granite, or alaskite. Many have small irregular pegmatitic phases and miarolitic (Section 12.0) cavities. Such features are taken to reflect a late tectonic stage of intrusion; the bodies are evidently post-deformational. These features may account for the absence of fractures at a suitable stage for the development of pegmatite

dykes. There is, however, no general agreement on the relationship between the distribution of pneumatolytic-hydrothermal deposits and the processes of pegmatite development.

The mine on Mont Antero, Colorado, which is not currently producing, consists of bertrandite-and beryl-bearing quartz veins, and beryl in sericitic greisen. Molybdenite and fluorite are also found in the greisens. The Boomer mine, once operated by the U.S. Beryllium Corporation at Badger Flats, Colorado, was also hosted by greisenized rocks. The mine was located close to the contact of a granitic batholith with Precambrian schists and gneisses. The metamorphic rocks are intruded by pegmatites of simple composition and by small granite plugs which are younger than the main batholith. The mine was actually located in one of the small fine-grained granite intrusions. The country rocks and greisens are transected by fluorite veins which are, however, devoid of beryllium.

3.5.2.3 Nonpegmatitic - disseminated replacement deposits

This group of beryllium deposits and/or occurrences has some features in common with the previously described nonpegmatitic deposits but also differs from them in several significant ways. The beryllium minerals are fine grained and are disseminated through the country rock. The deposits are spatially related to granitic or syenitic rocks and are considered to be replacement deposits of metasomatic origin. The chemical composition of the host rocks is undoubtedly a major factor in their development.

The principal producer of beryllium in the U.S.A. is Brush Wellman Inc. The company produces bertrandite ore from its Spor Mountain open pit mine in Utah and processes that ore (as well as imported beryl) into beryllium hydroxide at its Delta, Utah mill. The deposit has been classified as

a disseminated replacement deposit, and consists of bertrandite disseminated in rhyolite tuff of Miocene age. The tuff bed is part of a sequence of Cenozoic rhyolitic volcanic rocks that overlie Paleozoic volcanic rocks. The bertrandite is extremely fine grained and is most abundant in nodules several inches in diameter composed mainly of cryptocrystalline silica, fluorite, minor clay minerals and manganese oxides. Most of the clay is montmorillonite, which locally contains beryllium. Dolomite pebbles and cobbles found in a zone beneath the beryllium-enriched ore probably acted as a precipitating agent for beryllium derived from rhyolitic minor intrusions and transported in solution through fractures. The porosity and permeability of the tuff was probably responsible for its mineralization. The largest orebody ("Roadside") is a zone approximately 1500 by 200 by 4 metres thick, where approximately 2.7 million tonnes of ore containing 0.4 to 1.0% BeO have been delineated. The beryllium content is largely soluble in acids. Fluorite-rich pipes have been mined and a uranium-bearing deposit is located within 1.5 kilometres of the beryllium deposit. Also in the vicinity are rhyolite-hosted topaz and beryl occurrences.

In November of 1984, Emery Energy Inc. acquired Moody Beryllium Corp. which owned a beryllium deposit near the Spor Mountain deposit. Emery intended to develop the deposit, which contains 0.5 million tonnes of ore grading 0.64% BeO.

Two additional deposits, located in Canada, have been or are undergoing evaluation. The Iron Ore Company of Canada has studied the Strange Lake deposit on the Newfoundland-Quebec border. This high-grade yttrium and zirconium deposit also contains beryllium silicate and apparently could yield by-product beryllium. At Thor Lake, in the Northwest Territories, Highwood Resources Ltd. is evaluating a rare earth-beryllium-tantalum-columbium deposit. Of the two deposits, it appears that the Thor Lake deposit is more likely to be put into production

in the near future.

3.6 New Brunswick Potential

3.6.1 Occurrences

Crocco (1975) summarized the information available to that date on felsic intrusive (granitic) rocks in New Brunswick. Included are chemical and petrographic data for the various intrusions. Of the 123 beryllium analyses cited, ranging between "not detectable" and 15 ppm, 4 samples had values greater than 4 ppm and 110 samples had values less than 2 ppm. The Burnthill stock (Section 12.0) yielded one value of 5 ppm and one of 15 ppm, the Trout Lake stock yielded one value of 5 ppm and the Dungarvon stock yielded one value of 4 ppm. The 4 anomalous values therefore originated from 3 intrusive bodies (Plate 1) of close spatial and geologic relationship in an area, as will be discussed, known to host beryl occurrences.

3.6.1.1 Zealand Station (46°03':66°57')

Lutes (1981) reiterated Poole's identification of an occurrence of disseminated molybdenite associated with tourmaline and beryl in pegmatite and aplite (Section 12.0) within the Hawkshaw Granite west of Zealand Station.

Warner (1986) states that beryllium mineralization appears to be controlled by fracturing and/or shearing and that large crystals of beryl were noted in a quartz-orthoclase pegmatite. This property is currently held under mineral claim by Shediak Bay Resources Inc. and is undergoing evaluation.

3.6.1.2 Burnthill Mine and vicinity ($46^{\circ}35':66^{\circ}50'$)

Crouse (1981) summarized R.R. Potter's description of the geology of the Burnthill tungsten deposit. Beryl is associated with two of the three recognized vein types, one of which includes greisen dykes, and one of the two main mineral assemblages (quartz-beryl-molybdenite) identified in the deposit. Beryl is found near the margins of the greisen dykes; the dykes themselves are concentrated at a distance of at least 30 metres above and below a body of quartz monzonite. Crosby (1976) describes beryl in quartz veins intersected in drill core recovered from the Burnthill Mine site. Smith (1961) found beryl in mine waste, characteristically as radiating bursts of slender needles up to 5 centimetres long, associated with quartz, wolframite, topaz and molybdenite. Irrinki (personal communication, 1988) indicates that the deposit includes relatively large (3m thick) fluorite veins.

Irrinki (1981) identified the Trout Brook, Sisters Brook, Burnthill, Rocky Brook, Buttermilk Brook and Dungarvon stocks (Plate 1) as being favourable for hosting mineralization similar to that at the Burnthill deposit. Three areas in particular were noted, characterized by numerous quartz veins and greisen alteration of the Burnthill type. They are: the northwestern part of the Todd Mountain and Vicinity map area (L-16), near the Buttermilk Brook stock; around and within the Rocky Brook stock in the Rocky, Sisters and Clearwater Brooks map-area (L-15); and the northeastern and southwestern margins of the Trout Brook stock in the Todd Mountain and Vicinity map-area (L-16).

Tin exploration undertaken along the northeastern margin of the Trout Brook stock by Kidd Creek Mines Ltd. (Jensen, 1986) produced several bedrock analyses of beryllium, ranging between 4.5 and 1260 (0.13%) ppm. Mining claims, staked on

the basis of anomalous tin concentrations in till, straddled the plutonic/sedimentary rock contact and included outcrops of greisenized granite and greisenized fluorite veins.

Gardiner and Garnett (1986a and 1986b) have mapped the Dungarvon, Rocky Brook and Trout Brook stocks as different phases of a continuous unit, and refer to the Rocky Brook and Trout Brook "lobes" of the Dungarvon stock. Along the eastern margin of these two lobes are numerous occurrences of beryl, fluorite and greisen.

3.6.1.3 Beaver Brook Lake and South Burnthill Brook (46°45':66°55')

Crouse (1981) mapped an augen granite along the Catamaran Fault in the Parts of Burnthill and Clearwater Brooks map-area (K-14) and straddling the border between that map-area and the Lower Part of Burnthill Brook (K-15) map-area. Aplite and pegmatite are common throughout the augen granite and form concordant and discordant veins and dykes up to 2 metres thick. They contain, in order of abundance, potassium feldspar, quartz, muscovite, biotite, garnet and beryl.

Crouse (1981) also mapped pegmatite within the pink, biotite-muscovite phase (Unit Df_{2b}) of the Lost Lake Granite south of the Catamaran Fault. The pegmatite is found in narrow veins or in dykes over 1.5 metres wide and is composed of over 60% potassium feldspar, 10-20% muscovite, 5-20% quartz and 5-10% plagioclase. The pegmatite usually has a finer grained marginal phase in which red garnet is abundant. Beryl and tourmaline have also been observed in some of the pegmatite veins. A boulder of garnetiferous pegmatite situated just south of Burnthill Brook in northwest map-area K-15 contains garnets with diameters up to 1.5 mm and a large radiating beryl crystal over 17 cm long.

3.6.1.4 Juniper Station ($46^{\circ}33':67^{\circ}10'$)

Crocco (1975) reported traces of molybdenite in quartz veins cutting paragneiss xenoliths within granite located 4 kilometres northeast of Juniper Station and small pegmatite dykes cutting paragneiss along Highway 107, 3.25 and 5.6 kilometres east of Nashwaak Mountain. The area is known to host pegmatites which have been reported by several prospectors and geologists familiar with the area. Beryl crystals are reported to be associated with some of the pegmatites.

3.6.1.5 Pabineau Lake ($47^{\circ}30':65^{\circ}45'$)

Crocco (1975) reported molybdenite and beryl disseminated within granite cut by molybdenite-bearing quartz veins and fractures. Sheaves of green beryl crystals, 0.6 by 7.5 centimetres in size, were reported by Smith (1961). The occurrence is located 15 kilometres southwest of Bathurst and approximately 610 metres northwest of Pabineau Lake.

3.6.1.6 Square Lake ($45^{\circ}27':66^{\circ}23'$)

Smith (1961) reported seventeen showings of wolframite and molybdenite, with some associated beryl, over an area of less than seventeen square kilometres in the Square Lake area near the eastern margin of the Saint George Batholith. Mineralization is found in quartz veins and topaz greisen veins cutting the granite.

3.6.1.7 Others

Ruitenbergh and McCutcheon (1982) cite anomalous litho-

geochemical beryllium contents associated with tungsten, tin, molybdenum and fluorine at several mineral occurrences/deposits. These tungsten-molybdenum and tin +base metal sulphide-bearing greisen deposits are predominantly associated with granitoids and related subvolcanic intrusions ranging in age from Late Devonian to Early Carboniferous. In the central part of the province they cite the Rocky Brook ($46^{\circ}37':66^{\circ}37'$), Sisters Brook ($46^{\circ}39':66^{\circ}40'$), Todd Mountain ($46^{\circ}35':66^{\circ}40'$) (associated with the Trout Brook pluton), Burnthill, Cleveland prospect (associated with the Dungarvon pluton) and Sisson Brook ($46^{\circ}25':67^{\circ}04'$) areas. In the southwestern portion of the province, in and around the Saint George Batholith ($45^{\circ}20':66^{\circ}45'$), they cite the Pleasant Ridge, Howard Mountain, Deer Lake, Victoria Lake, Mistake Lake and Square Lake areas. As mentioned previously, visible beryl is present in the Rocky Brook, Sisters Brook, Todd Mountain, Burnthill and Square Lake areas.

Fyffe (1982) notes several beryllium occurrences, presumably beryl, referred to previously. He has also indicated several fluorine/fluorite occurrences, independent of beryllium occurrences mentioned herein, which, given the association between beryllium and fluorine, should also be noted. They are found at McBean Brook ($46^{\circ}33':66^{\circ}39'$), Martins Bluff ($46^{\circ}52':66^{\circ}36'$) and Costigan Mountain ($46^{\circ}58':67^{\circ}02'$).

3.6.2 Areas of potential

3.6.2.1 Vicinity of the Burnthill and Dungarvon stocks

The propensity for anomalous lithogeochemical beryllium and beryl occurrences in the area hosting the Dungarvon, Sisters Brook, Rocky Brook, Trout Brook, Buttermilk Brook and Burnthill stocks naturally targets this general area as one of interest for beryllium exploration. The presence of granitic pegmatites,

both beryl and apparently non-beryl bearing, is well documented; however, the presence of nonpegmatitic beryllium occurrences is not nearly so well documented since beryllium analyses are scarce.

The relatively small size of pegmatite bodies in central New Brunswick, and the economics of hand-cobbing beryl in North America, casts doubt on the potential of producing beryllium from pegmatites. If, in fact, the individual size of the pegmatites in this area is such that the requisite volumes are not present on an individual basis then the question of their density of occurrence becomes important. A continuation of this reasoning leads into the "grey area" in the classification of beryllium deposits, i.e., between pegmatitic and nonpegmatitic types, and may require that the potential for a nonpegmatitic deposit in the Burnthill-Dungarvon area be considered.

Fyffe et al. (1981) have described the intrusive rocks in the area as coarse-grained equigranular biotite granites containing smaller volumes of quartz-feldspar porphyry, miarolitic cavities and minor granophyre (Section 12.0). The porphyritic phases have been interpreted as representing residual magma mobilized during a late stage degassing event. Local secondary muscovite, muscovite-bearing veins and muscovite-greisen are attributed to late stage hydrothermal activity.

A phase of the Lost Lake Granite in the Beaver Brook Lake-South Burnthill Brook area contains both biotite and muscovite, i.e., is consistent with the bi-micaceous mineralogy referred to in Section 3.5.2.2. Bedrock mapping indicates that a substantial proportion of the rock exposed here is pegmatitic and that several outcrops contain beryl. This suggests that a substantial proportion of the bedrock as a whole in these areas may be beryllium-bearing. The question remains as to whether beryllium mineralization may be sufficiently concentrated in a specific

zone to be of economic interest.

Beryllium is associated with the Burnthill tungsten deposit, as is fluorite, molybdenite and greisen dykes. Similar mineral occurrences are expected, based on observed local geology and mineralogy, around the Buttermilk Brook stock, around and within the Rocky Brook stock and on the northeastern and southwestern margins of the Trout Brook stock. Greisenization, and fluorite and beryl mineralization have been confirmed along the northeastern margin of the Trout Brook stock.

3.6.2.3 Juniper Barrens Granite

Fyffe et al. (1981) have described the intrusion hosting the beryl occurrences near Juniper Station as a medium-grained equigranular to subporphyritic (Section 12.0) biotite granite. They identified an eastern contact zone about 1 kilometre wide which, although composed of a xenolith-rich biotite-hornblende granodiorite, is veined by biotite-muscovite granite, tourmaline-muscovite granite and garnet-muscovite-pegmatite. It is suspected that the reported beryl occurrences may be associated with these veins. The potential of these occurrences depends upon how extensive these veins are and their beryllium content.

3.6.2.3 Others

The Pabineau Lake and Square Lake occurrences both exhibit beryllium and molybdenite mineralization associated with quartz veining in granite. Greisens have also been observed at Square Lake. The extent or grade of these occurrences is unknown.

The significance of the beryllium occurrences at

Sisson Brook, Pleasant Ridge, Howard Mountain, Deer Lake, Victoria Lake and Mistake Lake is not known. Similarly, the fluorine occurrences at McBean Brook, Martins Bluff and Costigan Mountain have not been investigated in any detail.

3.7 Processing

Pegmatites are not usually mined for their beryl content. Beryl is generally recovered as a coproduct of mining other pegmatite minerals such as feldspar, mica, lithium minerals, columbite, tantalite, and cassiterite. Such deposits yield varying quantities of cobbled beryl.

Mining is usually begun on an outcrop where commercial pegmatite minerals can readily be seen. Rock is hand cobbled for beryl and other valuable minerals, and as much barren rock as practicable is broken off with hand hammers. Sometimes the blasted rock is coarsely crushed and passed over belts so that the minerals can be hand sorted from it. The balance of the rock may be reduced further in size for concentrating the targeted minerals. Where conditions warrant, mechanized mining methods are used.

The Copaux-Kawecki process (fluoride process) and the Sawyer-Kjellgren process (sulfate process) are used to convert beryl to beryllium oxide.

The fluoride process requires the sintering of briquets composed of a beryl-sodium ferric fluoride mixture; leaching the sintered briquets with water; precipitating beryllium hydroxide with caustic soda; filtering; and then igniting the precipitate to form beryllium oxide.

The sulfate process requires melting beryl at about

1,625°C and quenching the melt in cold water to obtain a glass; drying, grinding, and then leaching the glass with strong sulfuric acid; extracting beryllium and aluminum sulfates with water; and precipitating most of the aluminum with ammonium sulfate. Beryllium is then precipitated as a hydroxide by further chemical treatment and ignited to form beryllium oxide. Liquid-liquid extractions of beryllium may also be used to replace the complex chemical treatment following acid dissolution of the ore.

The Sawyer-Kjellgren sulfate process can be used to convert coarse beryl ore but is not suitable for converting low-grade and nonberyl ore or fine-grained concentrates. The Copaux-Kawecki fluoride process can be adapted to the use of finely ground ore and flotation concentrates.

The Brush Wellman Co. Inc. mines (nonpegmatite) bertrandite ore by open pit methods near Delta, Utah. The ore is wet-ground and screened to form a slurry that is transported to the processing plant where it is leached with a 10-percent sulfuric acid solution. The insoluble residue is filtered and discarded. The remaining beryllium sulfate solution is treated by a solvent-extraction process using di-2-ethylhexyl phosphoric acid in kerosene. The beryllium in solution is subsequently converted to beryllium hydroxide for further processing to the oxide or metal.

To obtain metallic beryllium, impure beryllium oxide is dissolved in an aqueous solution of acid ammonium fluoride. The resulting ammonium-beryllium fluoride is heated to expel the ammonia, leaving a residue of beryllium fluoride, which is reduced with magnesium in a graphite-lined furnace. A stoichiometrically deficient quantity of magnesium is used, and the excess beryllium fluoride acts as a flux that allows reaction at lower temperatures. The beryllium floats on the molten slag permitting separation after solidification. Excess beryllium

fluoride is returned to the operating cycle.

Beryllium usually is fabricated by powder metallurgy techniques because very coarse grains tend to develop in the castings, causing brittleness and low tensile strength. Clean, vacuum-cast ingots are converted into chips by machining, and the chips are ground to a powder in an inert atmosphere. The powder is compacted into dense, fine-grained bodies, usually by hot-pressing under a vacuum. The overall efficiency of processing beryl to beryllium metal is approximately 60 to 65%.

Beryllium-copper alloy, the major alloy used by the industry, is produced in an electric arc furnace at 1,800 to 2,000°C. A charge consisting of beryllium oxide, carbon and copper is reacted to produce a copper-base alloy containing 4 to 4.25% beryllium. After further refining, this master alloy is diluted with copper to a wide variety of commercial alloys. The overall efficiency of processing beryl to beryllium-copper master alloy is approximately 70%.

Energy requirements for beryllium materials production are high. Processing requires the use of induction furnaces that consume large quantities of energy. It is estimated that the production of 1 tonne of beryllium-copper master alloy requires approximately 1,100 million BTU.

Beryllium dust and fumes, even in small concentrations, have been recognized as the cause of berylliosis, a serious chronic lung disorder. Cases have been reported in communities surrounding beryllium processing plants. Control of potential health hazards adds significantly to the final cost of beryllium materials.

3.8 Strategic resource developments

The nonberyl based production from Utah is expected to stimulate interest in other nonberyl deposits.

4.0 Gallium

4.1 Properties

Gallium metal is silvery white in its high-purity state. Its atomic number is 31; atomic weight, 69.72; melting point, 29.78°C; boiling point, 2,403°C; and densities, 5.903 g/cm³ at 29.6°C (solid), 6.095 g/cm³ at 29.8°C (liquid) and 5.445 g/cm³ at 1,100°C. Other properties include expansion upon solidifying, 3.2%; specific heat from 12.5°C to 200°C, 0.295 calories/g/°C; and latent heat of fusion, 19.16 calories/g.

4.2 Saleable Forms and Price

The American Metal Market quotes 1985 prices for gallium in five forms.

1) 99.99999% - pure gallium metal	\$US525/kg
2) 99.9999% - pure gallium metal	\$US430-460/kg
3) 99.99% - pure gallium metal	\$US435/kg
4) 99.99% - pure gallium oxide	\$US380-400/kg
5) 99.999% - pure gallium oxide	\$US415/kg

Prices are quoted for 100 kilogram lots.

4.3 Production Statistics

Gallium is produced principally as a by-product from the processing of certain aluminum and zinc ores. Therefore figures for its production indicate principally the location of these processing facilities and not of gallium mining operations. Discrepancies exist between the various sources of gallium production figures, and the U.S. Bureau of Mines quotes its

figures as "estimated". Estimates for current total world production of gallium metal vary between 30 to 50 tonnes.

The following table is based upon various sources of gallium production figures; it should not, however, be treated as a definitive listing.

	1973	1981	1982	1983	1984	1985
	(kilograms)					
North America						
U.S.A.	W	1,500	1,560	nr	nr	nr
Canada	2,250	na	na	2,000	na	na
Europe						
France	na	na	na	2,500	na	na
W. Germany	na	na	na	3,000	na	na
Hungary	na	na	na	500	na	na
Switzerland	8,000	na	na	na	na	10,000(?)
Italy	300	na	na	na	na	na
Other	na	na	na	700	na	na
Asia						
China	50	na	na	2,000	na	na
Japan	100	8,000	7,000	8,000	17,000	19,000
Other	na	na	na	2,500	na	na

w - withheld
 nr - none reported
 na - not available

4.4 Uses

4.4.1 Applications

Gallium compounds such as arsenides, aluminum-arsenide, arsenide-phosphide, indium-arsenide and phosphide are used in the manufacture of semi-conductors. Among the end uses of semi-conductors are integrated circuits which have a very

large potential for growth. In addition, semi-conductors are used in light-emitting diodes (LEDs), laser diodes, Gunn effect diodes for microwave applications, switching diodes, light detectors and photoelectric materials. In short, gallium semi-conductor compounds are used in a multitude of electronic devices. Gallium is also used as a superconductive material in various alloys and in a number of alloys as a substitute for mercury. Gallium-indium-tin alloys are used for sealing glass windows in vacuum systems. Other uses for gallium are as an additive to magnesium where it increases the hardness of the resultant alloy at high temperature and as a constituent in cadmium and titanium alloys. Gallium is also used as a mirror coating in optical applications.

4.4.2 Alternatives

Alternative materials to gallium are available in almost all semiconductor applications. Silicon, germanium, and indium compounds are less costly compared to gallium arsenide. Generally, the superior performance of gallium in such applications as solid state devices and LED usually works in favour of the metal.

4.5 World Deposits

4.5.1 Gallium Geochemistry and Mineralogy

Two independent minerals of gallium are known. The sulphide gallite (CuGaS_2) found in southwest and central Africa and the hydroxide, soehngeite ($\text{Ga}(\text{OH})_3$). Neither mineral has been found in concentrations capable of supporting their extraction.

The distribution of gallium is dominantly attributable

to its close relationship with aluminum in magmatic processes and to the cycle of weathering and sedimentation. As a result, gallium is recovered as a by-product from the extraction of aluminum from bauxite. In addition, under low temperature hydrothermal conditions, gallium substitutes isomorphically for zinc in sphalerite (ZnS). As a result, gallium is also recovered as a by-product from zinc refining of certain sphalerite ores.

4.5.2 Deposit Classification

4.5.2.1 Bauxite

Gallium is a widespread element in nature but as stated is only very rarely found compounded in its own minerals. Gallium is frequently associated with aluminum in common rock-forming minerals such as some feldspars, amphiboles and micas. Intense weathering of magmatic rocks rich in these minerals tends to concentrate aluminum and gallium. Gallium, however, is more mobile than aluminum and as a result the ratio of gallium to aluminum usually decreases in the products of weathering. Although there is some separation of gallium and aluminum in weathering processes, the coherence between the elements yields a high correlation between their concentrations in clays and bauxites. Processing of bauxites for the production of aluminum yields as a by-product the bulk of the world's supply of gallium. Bauxites are known to contain up to 0.01% of gallium.

4.5.2.2 Sphalerite

Under certain hydrothermal conditions, gallium substitutes isomorphically for zinc. The content of gallium in sphalerite is related to both the geological province and the temperature of formation. Under low temperature hydrothermal conditions

especially where associated phases have little affinity for gallium, such as in quartz-fluorite veins, gallium tends to concentrate in sulphides. Gallium will concentrate in sphalerite where it is associated with carbonate rocks, whereas it tends to disperse when sulphide ores are deposited in silicate country rocks. The gallium content of such sphalerites range from 0.001 to 0.02%.

4.5.2.3 Others

The Apex Mine in Utah, U.S.A. is the only mine in the world operated primarily for germanium and gallium production. The ore, consisting of goethite, limonite, hematite, jarosite, azurite, malachite, conichalcite and several other metallic oxides, carbonates, arsenates and sulphates, is thoroughly oxidized to at least 425 metres below surface. Gallium is concentrated mostly in jarosite and in some limonite. The ore forms irregular, branching chimney-like bodies in fault breccia (Section 12.0), gouge zones and fissures associated with steeply dipping subparallel faults within Pennsylvanian limestone. Within and immediately adjacent to the fault zones, limestone has been dolomitized and locally silicified.

Analysis of coal ash and flue dust from coal consuming plants indicate that gallium is concentrated in coal. Up to 0.1% gallium has been reported, but is usually much less. The way in which gallium is incorporated in coal is uncertain. Some workers believe that it is due in part to an association with the lighter alumino-silicate minerals (clay minerals) often found in intimate association with coals. There is evidence, however, that organometallic complexes containing gallium do exist. The only known commercial extraction of gallium from coal dusts was by Johnson Matthey in the U.K. Until 1970 gallium was recovered as a by-product of germanium extraction.

The Thor Lake beryllium deposit near Yellowknife, N.W.T., which is being evaluated by Highwood Resources Ltd., has gallium associated with it. A zone, separate from the main orebody, contains 1% niobium oxide and 0.05% gallium and the deposit wall rocks contain beryllia, yttria, rare earths and 0.05% gallium oxide over 10 metres.

4.6 New Brunswick Potential

4.6.1 Occurrences

4.6.1.1 Oil Shale

Abbott and Barnett (1968) cite an average of 0.001% gallium in 14 oil shale samples collected from the Albert Formation at Albert Mines ($45^{\circ}53':64^{\circ}40'$). Pickerill and Carter (1980) cite 18 oil shale analyses from three sample locations, the Albert Mines deposit and the Rosevale and Urney areas, all with undetectable quantities of gallium.

4.6.2 Areas of Potential

Several geological and mineralogical indicators are useful in the exploration for gallium deposits. Gallium in epigenetic (Section 12.0) low-temperature sphalerite deposits in carbonate host rocks, particularly in those containing organic material, warrant exploration attention.

Gallium is sometimes enriched during supergene (Section 12.0) processes, becoming particularly concentrated in iron oxides and hydroxides and more rarely in arsenates and hydroxy-sulphates. Due to this supergene enrichment, the limonite and related material of oxidized gallium-bearing copper-iron sulphide

deposits (gossan, Section 12.0), which is generally considered as waste, may contain concentrations of gallium.

The association of gallium with carbonate-hosted sphalerites indicates that exploration for and evaluation of such zinc occurrences should include analyses for gallium. Such occurrences which are known in New Brunswick are those at Memramcook East ($46^{\circ}00':64^{\circ}31'$), Curryville ($45^{\circ}50':64^{\circ}38'$), Titusville ($45^{\circ}29':65^{\circ}45'$), Cedar Camp ($45^{\circ}42':65^{\circ}49'$), Piccadilly ($45^{\circ}44':65^{\circ}20'$), Peekaboo Corner ($45^{\circ}40':65^{\circ}43'$) and Midland ($45^{\circ}40':65^{\circ}47'$) (Wilson and Ball, 1983). None of these occurrences, however, appear in themselves to be anything more than small sphalerite occurrences.

4.7 Processing

Commercial production of gallium has historically been primarily from aluminum ores and to a lesser extent from zinc ores.

4.7.1 Alumina

The bulk of current production of aluminum is from alumina (aluminum oxide) which is produced from bauxite. The Bayer process for extracting alumina from bauxite relies on the reaction of aluminum trihydroxide and aluminum oxide hydroxide with aqueous caustic soda to form sodium aluminate. The sodium aluminate solution (Bayer liquor) is continuously recycled; this results in the gallium building up to a concentration of 0.25% to 0.70%. Gallium can be extracted from the Bayer liquors by electrodeposition or electrolysis. In the Pechiney process (used by Pechiney in France) and the Frary process (which was formerly used by Alcoa in the U.S.A.) gallium is

kept in solution while other dissolved species are precipitated, and when the solution is sufficiently concentrated, gallium is obtained by electrodeposition. In the de la Breteque process (which was developed by Alusuisse) gallium is extracted by direct electrolysis, using strongly agitated mercury cathode in which the gallium accumulates. Gallium is extracted from this with sodium hydroxide and electrolysis. This process has not been widely adopted because of its use of mercury. The Bielfeld and Laspeyers process used by VAW in West Germany is similar to the de la Breteque process.

Several new processes for recovering gallium during alumina production are under development, and some have been reported. The British Aluminium Company (now British Alcan) has developed a method of alloying gallium with tin by electrolysis, and then separating it by alkali fusion. Reynolds has researched a method for concentrating gallium in aluminate by adding silica to extract an aluminum silicate. Other new methods are being investigated in the U.K., in France, in the U.S.A., in Czechoslovakia, and in the U.S.S.R. Increasing demand for gallium has prompted many organizations throughout the world to attempt to improve on existing extraction methods, and to look at other sources of gallium apart from Bayer process liquors.

Initial recovery of gallium, from Bayer process liquors or other sources, yields a product of up to 99.9% purity. Vacuum heating removes metal oxides to give 4N gallium. Higher purities are obtained by forming and zone-refining gallium trichloride, or by recrystallisation of molten gallium.

4.7.2 Zinc

Historically, the smelting of zinc concentrates was

carried out in horizontal retorts, in which the zinc is distilled off, and residues containing gallium and germanium are fired in a Waelz kiln so that gallium is volatilized. The gallium accumulates in the flue dusts, and can then be recovered. The electrolytic zinc process superseded this method; zinc sulphide concentrates are roasted to produce zinc oxide. This is leached by sulphuric acid to dissolve the zinc oxide as zinc sulphate. The impurities are separated from the leach solution by the addition of zinc dust and antimony trioxide or arsenic trioxide; gallium is recovered from the electrolytic precipitate.

4.7.3 Scrap

Scrap is a very important source of gallium. Wastage in the manufacture of wafers of gallium arsenide or gallium phosphide from single crystals are substantial and there is further wastage at each subsequent stage of manufacture of electronic devices. Some of the gallium contained in this scrap is recoverable.

4.8 Strategic Resource Developments

The major development in gallium production was the opening in 1986 of Musto Exploration Ltd.'s Apex Mine in Utah, U.S.A. This mine is the first and only producer in the world operated primarily for germanium and gallium. Full production of the mine and recovery plant located near St. George, Utah reportedly amounts to 10 tonnes of gallium and 17.9 tonnes of germanium per year.

In 1986, Rhone-Poulenc of France announced its intention to begin construction of a new gallium refinery in Australia. The refinery will process material from Alcoa's alumina operations and will have a capacity in excess of the total current world production.

5.0 Germanium

5.1 Properties

Germanium has a metallic appearance, is grayish-white in colour, lustrous, hard, and very brittle, and exhibits the properties characteristic of metals only under certain conditions. It is a semiconductor with properties between those of a metal and an insulator. Some physical properties of germanium are: atomic number 32, atomic weight 72.59, density 5.36 grams per cubic centimetre at 20°C, melting point 937.4°C (1,719°F), and boiling point approximately 2,830°C (5,125°F); electrical resistivity of intrinsic germanium at 27°C is 46 ohm-centimetres. Germanium is insoluble in water, hydrochloric acid, and dilute alkali metal hydroxides. It is soluble in aqua regia, in concentrated nitric and sulfuric acids, and in fused alkalies, alkali peroxides, nitrates, and carbonates.

5.2 Saleable Forms and Price

Domestic U.S. germanium producer prices, published by Metals Week, for germanium metal and germanium dioxide in 1985 were \$US1060 and \$US660 per kilogram, respectively.

Germanium is marketed in three forms, as reduced ingots, purified ingots and single crystals. Standard ingots are 38 to 43 centimetres long and weigh approximately 1.75 kilograms. Single crystals are supplied in sizes up to 7.5 centimetres in diameter and weighs up to 2 kilograms.

5.3 Production Statistics

Germanium is produced principally as a by-product

from the processing of certain zinc and copper ores. Therefore, figures for its production indicate principally the location of these processing facilities and not of germanium mining operations.

	1981	1982	1983	1984	1985
	(kilograms)		avg.		
North America					
U.S.A.	na	na	21,000	22,000	
Europe					
Austria	4,000	4,000	6,000	4,800	5,000
Belgium	na	na	19,000		na
France	na	na	11,000		na
Italy	na	na	10,000		na
W. Germany	na	na	9,000		na
Asia					
Japan	11,000	7,000	7,000	8,000	10,000
Other (Centrally Planned)	na	na	18,000		na

na - not available

5.4 Uses

5.4.1 Applications

A significant user of germanium is the manufacture of semi-conductor devices which have widespread application in the electronics industry, including LED's. Germanium has important applications in metallurgy, chemotherapy, polymer chemistry and optical instrumentation. The latter end use is becoming increasingly important particularly with recent developments in fiber-optics telecommunications. Germanium is incorporated in devices designed to detect nuclear radiation. In metallurgy

it is used to improve the hardness properties of metal alloys that contain copper, aluminum and magnesium. Small amounts are alloyed with gold for special precision castings and as solder in jewelry manufacturing. Germanium is used extensively as a catalyst to produce synthetic fibers.

Infrared optics, especially for military use in guidance and weapon-sighting systems is the largest end use of germanium in the U.S. Germanium-bearing lenses and windows transmit thermal radiation in a manner similar to visible light transmission by optical glass. Germanium is an important constituent in many fiber-optic cables which are replacing conventional wire telecommunication systems.

5.4.2 Alternatives

An increasing amount of silicon, which is less expensive than germanium, is being used in various electronic applications. Although germanium is more reliable in a number of high-frequency and high-power applications and more economical as a substrate for some LED applications, several bimetallic compounds of tellurium, selenium, indium, and gallium may be applied. In infrared optics, zinc selenide for germanium glass can be substituted, but at the expense of performance.

5.5 World Deposits

5.5.1 Germanium Geochemistry and Mineralogy

Germanium is widely dispersed as a trace element within the earth's crust and is present in many different substances, but only at very low concentrations. The geochemistry of germanium is such that it is able to assume lithophile,

chalcophile or siderophile properties under different geological conditions. In the formation of igneous rocks, germanium is lithophile; that is, displays a strong affinity for oxygen and is thus enriched in the silicate crust of the earth. Chalcophile tendencies, however, are predominant in hydrothermal processes, where germanium exhibits a strong affinity for sulphur. Under certain conditions germanium is also siderophile and associates with iron. Germanium rarely forms minerals of its own, but when it does its concentration in those minerals is generally less than 8 or 9%.

Germanium is found in two sulphide minerals of economic significance: renierite, $(6-8\% \text{ Ge}) \text{Cu}_{10}(\text{Zn}_{1-x}\text{Cu}_x)\text{Ge}_{2-x}\text{As}_x\text{Fe}_4\text{S}_{16}$ and germanite, $(5\% \text{ Ge}) \text{Cu}_{11}\text{Ge}(\text{Cu}, \text{Zn}, \text{Fe}, \text{Ge}, \text{W}, \text{Mo}, \text{As}, \text{V})_{4-6}\text{S}_{16}$. Briartite, the germanium equivalent of stannite-kesterite, $\text{CuSn}(\text{Fe}, \text{Zn})\text{S}_4$ is found associated with tennantite, $(\text{Cu}, \text{Fe}, \text{Zn}, \text{Ag})_{12}\text{As}_4\text{S}_{13}$ in deposits containing renierite and germanite. The sulphide argyrodite $(5-7\% \text{ Ge}), \text{Ag}_8\text{GeS}_6$, is the mineral in which germanium was first discovered, but is of no economic significance. Germanium substitution in the zinc sulphide, sphalerite, results in sphalerite being the major source of germanium. Specifically, sphalerites in low-temperature epigenetic deposits, particularly those in sedimentary rocks, contain germanium concentrations up to 0.3%.

A number of other sulphides contain germanium in metallic substitution. Germanium is associated with several tin bearing sulphides including canfieldite, stannite and colusite and has been identified in tin bearing sulphosalts such as teallite. High concentrations of germanium are also often reported from enargite, Cu_3AsS_4 .

Germanium oxides and hydroxides are known in oxidized zones of mines yielding germanium sulphides. The hydroxides stottite, $\text{FeGe}(\text{OH})_6$, mangan-stottite $\text{MnGe}(\text{OH})_6$ and a zinc bearing

variety, $\text{FeZnGe}_2(\text{OH})_{12}$ have been documented. Argutite, GeO_2 has been found as inclusions in sphalerite and brunogeierite, Fe_2GeO_4 has been found in germanium bearing sphalerite deposits. Magnetite, Fe_3O_4 , particularly that from skarns is often found to be enriched in germanium although only to levels of 0.0003%. Considerable substitution of germanium for tin can occur in cassiterite, SnO_2 : up to 0.3% in epigenetic coarsely crystalline varieties. The iron oxides goethite, HFeO_2 and hematite, Fe_2O_3 also have large capacities for incorporating germanium, particularly in the oxidized zones of germanium bearing sulphide deposits. The minerals bartelkeite, $\text{PbFeGe}_3\text{O}_8$ and otjisumeite, PbGe_4O_9 are classed as germanates.

Germanium is frequently concentrated in coal and the unnamed mineral GeS_2 has been found forming around gas vents in burning coal piles in Pennsylvania.

5.5.2 Deposit Classification

5.5.2.1 Sphalerite

The primary commercial production of germanium is from carbonate and shale hosted sphalerite rich sulphide deposits. These include the upper Mississippi Valley district in the U.S.A. and the Saint-Salvy sphalerite deposit in France.

5.5.2.2 Copper-Lead-Zinc Sulphides

Production is also derived from germanium rich zones within high-grade copper ores of copper, lead and zinc sulphide deposits in Africa. The Kipushi orebody in Zaire forms a highly irregular subvertical pipe at the faulted boundary of dolomitic shale and marine dolomite, with sulphide replacement zones

extending along bedding planes and fracture zones. Renierite in particular is locally abundant. The Tsumeb orebody in Namibia consists of an irregular pipe-like body within late-Precambrian dolomite. Germanite-rich masses are present.

5.5.2.3 Others

The Apex Mine in Utah, U.S.A. is the only mine in the world operated primarily for germanium and gallium production. The ore, consisting of goethite, limonite, hematite, jarosite, azurite, malachite, conichalcite and several other metallic oxides, carbonates, arsenates and sulphates, is thoroughly oxidized to at least 425 metres below the surface. Germanium is concentrated chiefly in goethite, hematite and limonite. The ore forms irregular, branching chimney-like bodies in fault breccia, gouge zones and fissures associated with steeply dipping subparallel faults within Pennsylvanian limestone. Within and immediately adjacent to the fault zones, limestone has been dolomitized and locally silicified. The deposit is the highly oxidized equivalent of the Kipushi and Tsumeb orebodies.

The United Kingdom used to, but apparently no longer extracts some germanium from the coal ash and flue dust which results from the combustion for electrical power generation of germanium rich coals. The only known commercial extraction of germanium from coal dusts was by Johnson Matthey, which ceased production in 1970.

5.6 New Brunswick Potential

5.6.1 Occurrences

5.6.1.1 Oil Shales

Abbott and Barnett (1968) cite an average of less

than 0.001% germanium in 14 oil shale samples collected from the Albert Formation at Albert Mines. They also cite one analysis of albertite at 0.01% and another at 0.025% germanium.

5.6.1.2 Coal

Abbott and Barnett (1968) cite an average of 0.012% germanium in 8 coal ash samples collected, presumably, from the Minto-Chipman coalfields.

5.6.2 Areas of Potential

Several geological and mineralogical indicators could be useful in the exploration for germanium deposits. Germanium is most likely to be highly concentrated in copper-rich portions of hydrothermal sulphide deposits hosted by sedimentary carbonates, particularly in those containing coal or related organic material. The presence of high concentrations of arsenic, antimony, tin or possibly vanadium in such ores also increases the probability of germanium being present. Renierite, germanite, briartite, argyrodite, enargite and tin sulphides and sulphosalts are the chief germanium minerals in these ores. Germanium in epigenetic low-temperature sphalerite deposits within carbonate or shale host rocks, particularly in those containing organic material, warrant exploration attention.

Germanium is sometimes enriched during supergene processes, becoming particularly concentrated in iron oxides and hydroxides and more rarely in arsenates and hydroxy-sulphates. Due to this supergene enrichment, the limonite and related material of oxidized, germanium-bearing, copper-iron sulphide deposits (gossan), which is generally considered as waste, may contain concentrations of germanium.

The association of germanium with carbonate or shale-hosted sphalerites indicates that exploration for and evaluation of such zinc occurrences should include analyses for germanium. Known occurrences include those at Memramcook East, Curryville, Mount Whatley ($45^{\circ}53':64^{\circ}16'$), Titusville, Cedar Camp, Piccadilly, Peekaboo Corner and Midland (Wilson and Ball, 1983). In addition, there are a number of minor sedimentary lead occurrences, some associated with coal, which could contain sphalerite-germanium although neither is reported. These occurrences are found at Stonehaven, Caraquet, Norton (Wilson and Ball, 1983) and Cocagne (Ball *et al.*, 1981). None of these occurrences, however, appear in themselves to be anything more than small galena and/or sphalerite occurrences.

It is advisable that analyses for germanium be accompanied by analyses for gallium.

5.7 Processing

Germanium is obtained commercially as a by-product in base-metal refining. In its recovery from sulphide concentrates, the sulfur is first removed by roasting, and the zinc, germanium, and cadmium are converted to oxides. The oxides are given a chloridizing roast to convert cadmium and germanium to chlorides which are then volatilized. These are condensed and collected electrostatically to yield a product from which germanium can be distilled as the tetrachloride.

The copper-zinc ores of Zaire contain germanium in the mineral renierite. The renierite reports with the copper flotation concentrate and is then recovered by magnetic separation. This product is treated in an electric furnace to obtain a fume containing germanium dioxide. Germanium-bearing fume and dust are then baked and leached with sulfuric acid, after which

the germanium is precipitated with magnesia and copper hydrate as the crude oxide.

Flue dusts are smelted with sodium carbonate, lime, copper oxide, and coal dust to form a regulus and slag. The regulus, containing germanium, is reacted with chloride, and the crude germanium tetrachloride is then subjected to fractional distillation. When germanium is used as a semiconductor, it must be in the form of a single crystal of extremely high purity.

5.8 Strategic Resource Developments

The major development in germanium production was the opening in 1986 of Musto Exploration Ltd.'s Apex Mine in Utah, U.S.A. This mine is the first and only producer in the world operated primarily for germanium and gallium. Full production of the mine and recovery plant located near St. George, Utah reportedly amounts to 10 tonnes of gallium and 17.9 tonnes of germanium per year.

6.0 Rare Earth Elements and Yttrium

6.1 Properties

The rare earth elements (REE), lanthanum to lutetium (atomic numbers 57-71) are members of Group IIIA in the periodic table and all have very similar chemical and physical properties. This uniformity arises from the nature of their electronic configurations, leading to a particularly stable 3^+ oxidation state and a small but steady decrease in ionic radius with increase in atomic number for a given co-ordination number. Yttrium, having an atomic number of 39, is also a member of Group IIIA and shows a similar chemistry to that of the REE, so is often included with them.

The REE are divided into two sub-groups: those from lanthanum to europium having lower atomic numbers, being referred to as the light rare earth elements (LREE) or the cerium subgroup and those from gadolinium to lutetium having higher atomic numbers, being referred to as the heavy rare earth elements (HREE) or the yttrium subgroup.

	atomic #	
light rare earth elements:		
lanthanum	La	57
cerium	Ce	58
praseodymium	Pr	59
neodymium	Nd	60
promethium	Pm	61
samarium	Sm	62
europium	Eu	63
heavy rare earth elements:		
gadolinium	Gd	64
terbium	Tb	65
dysprosium	Dy	66
holmium	Ho	67
erbium	Er	68
thulium	Tm	69
ytterbium	Yb	70
lutetium	Lu	71
and		
yttrium	Y	39

6.2 Saleable Forms and Price

The rare earth elements do not occur in fixed ratios in their various source deposits. As a result surpluses of certain REE's exist for which there is little or no demand. Complex interrelationships among the REE's and among other elements such as yttrium and thorium, which are associated with some of the rare earth minerals cause supply-demand imbalances and wide fluctuation in the average price of rare earth products.

Monazite concentrates generally range from 55 to 65% REO (REE oxides). Chemical processing companies set individual requirements for purchase of monazite concentrate but generally specify at least 55% of contained REO. Bastnaesite concentrates average approximately 63% REO, but are upgraded to 72% REO by acid leaching and to 90% REO by a combination of leaching and calcining.

Oxides of the REE's are produced, traded and consumed as are various compounds. In addition, the REE metals and the common REE metallic mixture, mischmetal are marketed. Generally mischmetal has the same ratio of REE's as that found in the natural ore.

concentrates:

monazite, 55% REE + thoria, f.o.b. Australia	\$US580-614/ton
yttrium, 60% Y_2O_3 , f.o.b. Malaysia	\$US46/kg
yttrium, contained Y_2O_3	\$US51-63/kg
bastnaesite	
unleached, 60% REO, contained REO	\$US0.92/lb
leached, 70% REO, contained REO	\$US0.97/lb
calcined, 85% REO, contained REO	\$US1.17/lb
cerium, contained CeO_2	\$US1.40/lb
lanthanum, contained La_2O_3	\$US1.40/lb

oxides: 99.9%, 1-20 kg lots, f.o.b. Phoenix, AZ.

cerium	\$US20/kg
dysprosium	\$US110/kg
erbium	\$US200/kg
europium	\$US1900/kg
gadolinium	\$US140/kg
holmium	\$US650/kg
lanthanum	\$US19/kg
lutetium	\$US5200/kg
neodymium	\$US80/kg
praseodymium	\$US130/kg
samarium	\$US130/kg
terbium	\$US1200/kg
thulium	\$US3400/kg
ytterbium	\$US225/kg
yttrium	\$US118/kg

compounds:

cerium carbonate, 95%, 20 kg lots, f.o.b. Freeport, TX.	\$US8.60/kg
cerium hydroxide, 95%, 20 kg lots, f.o.b. Freeport TX.	\$US11.25/kg
cerium nitrate, 95%, 200 kg lots, f.o.b. Freeport TX.	\$US11.05/kg
cerium fluoride, tech. grade, 114 kg lots, f.o.b. York PA.	\$US5.50/kg
lanthanum carbonate, 99.5%, 20 kg lots, f.o.b. Freeport TX.	\$US12.60/kg
lanthanum-neodymium carbonate, 98%, 20 kg lots, f.o.b. Freeport TX.	\$US7.20/kg
lanthanum nitrate, 99.5%, 200 kg lots, f.o.b. Freeport TX.	\$US11.90/kg
lanthanum chloride, 46%, 239 kg lots, f.o.b. York PA.	\$US2.09/kg
lanthanum-lanthanide carbonate, 60%, 91 kg lots, f.o.b. York PA.	\$US5.39/kg
lanthanum-lanthanide nitrate, 39%, 114 kg lots, f.o.b. York PA.	\$US3.85/kg
neodymium carbonate, 95%, 20 kg lots, f.o.b. Freeport TX.	\$US7.75/kg
neodymium nitrate, 95%, 200 kg lots, f.o.b. Freeport TX.	\$US8.40/kg

metals: ingot form, 1-5 kg, from 99.9%
grade oxides, f.o.b. Phoenix AZ.

cerium	\$US125/kg
dysprosium	\$US300/kg
erbium	\$US650/kg
europium	\$US7500/kg
gadolinium	\$US485/kg

holmium	\$US1600/kg
lanthanum	\$US125/kg
lutetium	\$US14,200/kg
neodymium	\$US260/kg
praseodymium	\$US310/kg
samarium	\$US330/kg
terbium	\$US2800/kg
thulium	\$US8000/kg
ytterbium	\$US875/kg
yttrium	\$US510/kg
mischmetal, 99.9%	\$US12.32/kg

6.3 Production Statistics

	1981	1982	1983	1984	1985
	(tonnes)				
Monazite					
Australia	13,282	9,562	15,141	16,702	15,000 ^e
Brazil	2,460	1,814	5,256	3,622	6,000 ^e
China	na	na	na	na	na
India	3,704	4,000 ^e	4,000 ^e	4,000 ^e	4,000 ^e
Malaysia	320	582	1,051	4,451	5,808
Mozambique	4	3	4	4	4 ^e
Sri Lanka	60	304	300	147	200 ^e
Thailand	170	162	277	298	245
USA	1,420	1,670	1,670	2,500	2,500 ^e
Zaire	35	32	15	2	-
sub-total	21,450	18,129	27,714	31,726	33,757
Bastnaesite					
Burundi	50	-	-	-	-
China	na	na	na	na	na
USA	28,470	29,170	28,470	42,190	22,380
sub-total	28,520	29,170	28,470	42,190	22,380
Xenotime					
Australia	52	46	24	na	na
Malaysia	24	76	10	384	na
Thailand	45	46	38	28	24
sub-total	121	168	72	na	na
total	50,091	47,467	56,256	=74,328	=56,161

e - estimated
na - not available

6.4 Uses

6.4.1 Applications

One of the most important applications for rare earths is in chemical catalysis. Rare earth chlorides containing 1-5% REE's added to fluidized cracking catalysts, improve their structural and thermal stability, catalytic activity and processing selectivity in the production of petroleum end products. Cerium is used in automotive catalytic converters to help prevent catalytic degradation at high temperatures and to aid oxidation of pollutants under fuel-rich, oxygen-poor conditions. Other catalytic applications for REE include ammonia synthesis, water storage compounds for agriculture needs, hydrocarbon oxygenation reaction required in self cleaning ovens and in chlorine recovery from by-product of hydrochloric acid.

REE's in the form of mischmetal or cerium oxides are alloyed in steels to improve physical and rolling properties. Mischmetal (75%) and iron (25%) are used to produce lighter flints. Specialty alloys required by the permanent magnet industry consist of various rare earth compounds, particularly samarium oxide. Permanent magnets are employed in electrical components including disc drives for personal and main frame computers.

REE's are used as ingredients in glass when specific colours or hues are required. Cerium is used to stabilize glass against ultraviolet rays and is a major constituent in polishing compounds for precision optics. A minor use of rare earths is in phosphors for cathode ray tubes.

Recent research advances indicate that the development of economically viable alloys of rare earths capable of conducting electricity with essentially no conductor resistance may soon become a reality. Applications of these "super conductors"

range from superfast computers to much more efficient transmission of electricity.

6.4.2 Alternatives

In Europe, REE's in the form of mischmetal are in decline in the steel industry due to such technically superior materials as calcium compounds in special clay mixtures. Ultra-stable zeolites are replacing REE's in certain catalytic applications due to their ability to produce higher octane gasoline more efficiently. In general, REE's perform better than substitutes in glass decolourizing and polishing compounds.

6.5 World Deposits

6.5.1 Mineralogy

The crustal abundance of REE's varies markedly from element to element and with the exception of yttrium, the light sub-group members are far more abundant than the heavy sub-group members. Rare earth elements have been identified in approximately 100 mineral species. The following eight minerals account for most of the known REE concentrations.

1) Allanite is a complex REE-concentrating mineral $(Ca, Fe)_2 (LREE, Al, Fe)_3 Si_3 O_{13} H$ which may also contain HREE and yttrium. Allanite is a common accessory mineral in granitoid rocks and pegmatites. It is found as a product of metamorphism in rocks with felsic compositions.

2) Apatite is ubiquitous in mafic and felsic igneous rocks, sedimentary and metamorphic rocks. It is common in pegmatites. Apatites from silica-rich rocks tend to

be richer in HREE whereas apatites from silica-poor, alkali-rich rocks are LREE-rich. Sedimentary apatites in marine deposits are cerium deficient.

3) The bastnaesite-synchisite series are much more rare than allanite or apatite but are fairly common in alkalic igneous rock suites and in some metamorphic terrains. The mineral is usually LREE-rich and is found in commercially important amounts in carbonatite intrusions associated with other alkalic igneous rocks.

4) Fluorite is a REE concentrating mineral that is normally pure CaF_2 . It is a common, late-crystallizing mineral in granitoid rocks and pegmatites, especially in the more alkaline varieties. It favours HREE.

5) Monazite is a LREE mineral which is a common accessory of low abundance in many granitoid rocks and pegmatites and is often associated with xenotime. It is fairly resistant to weathering and metamorphic processes and can be concentrated in placer deposits.

6) Perovskite, CaTiO_3 , is a REE-concentrating mineral that tends to be complex, with several elements (Na, Fe, Th, U, Mn, REE) substituting for Ca and several (Nb, Ta, Fe, Mg, Zr) substituting for Ti. REE-rich varieties are mainly associated with alkalic igneous rock suites. It is enriched in LREE.

7) Sphene is a Ca,Ti mineral that in some cases concentrates REE. The REE-rich variety is sometimes an accessory mineral in coarse grained granitoid (or felsic igneous) rocks, in pegmatites and in some metamorphic rocks. They appear to be enriched in LREE.

8) Zircon, ZrSiO_4 , is a common, but sparse accessory mineral in alkaline igneous rocks and some pegmatites. It is fairly resistant to weathering and metamorphic processes and can be concentrated in placer deposits. Zircons accept a spectrum of REE's.

Four minerals are sufficiently rich in REE's and develop in such concentrations to be of particular economic interest. Monazite, $(\text{REE}, \text{Th}, \text{Y})\text{PO}_4$ and bastnaesite, $(\text{REE}(\text{CO}_3)\text{F})$, together have accounted for almost all of historical world production. Xenotime $(\text{Y}, \text{REE})\text{PO}_4$, which is produced in minor quantities, is the major source of yttrium and HREE. REE have also been recovered from brannerite, $(\text{U}, \text{Ca}, \text{Ce})(\text{Ti}, \text{Fe})_2\text{O}_6$ and euxenite $(\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6$.

	monazite REO(%)	bastnaesite REO(%)	xenotime REO(%)	apatite REO(%)
La_2O_3	23.7	33.2	0.5	25.1
CeO_2	45.6	49.1	5.0	45.0
Pr_6O_{11}	5.0	4.3	0.7	3.9
Nd_2O_3	17.2	12.0	2.2	14.0
Sm_2O_3	2.5	0.78	1.9	1.6
Eu_2O_3	0.05	0.11	0.2	0.5
light REO total	94.05	99.49	10.5	90.1
Ge_2O_3	1.5	0.17	4.0	1.5
Tb_4O_7	0.04	0.016	1.0	0.1
Dy_2O_3	0.68	0.031	8.7	1.0
Ho_2O_3	0.05	50 ppm	2.1	0.1
Er_2O_3	0.21	35 ppm	5.4	0.15
Tm_2O_3	0.02	8 ppm	0.9	0.02
Yb_2O_3	0.12	13 ppm	6.2	0.08
Lu_2O_3	0.04	1 ppm	0.4	-
Y_2O_3	2.4	0.09	60.8	4.3
heavy REO total	5.06	0.318	89.5	7.25

6.5.2 Deposit Classification

Rare earth minerals are found in a wide range of geological environments. The limited number of mined deposits reflects not only the comparative rarity of significant concentrations but also the current relatively small demand for the elements. REE are currently almost entirely produced from alkaline rocks, carbonatites and placer deposits. Other occurrences are of potential economic interest: apatite may be enriched in REE, particularly where associated with alkaline igneous rocks, and may provide a commercial source during the production of phosphoric acid for fertilizer manufacture.

6.5.2.1 Alkaline Igneous Rocks/Carbonatites

Many alkaline (Section 12.0) igneous rocks, particularly carbonatites (Section 12.0), are enriched in REE, both in rare earth minerals and by virtue of substitution within other minerals such as apatite and pyrochlore.

6.5.2.1.1 Africa

In Africa several REE-bearing carbonatites have been recognized and some have attracted commercial interest. Production has been confined to the bastnaesite-bearing veins at Karonge, southeast of Bujumbura in the Republic of Burundi. Here the REE mineralization, consisting mainly of bastnaesite and monazite, is found in veins and veinlets often forming a dense stockwork. Quartz, barite and geothite are the common gangue (Section 12.0) minerals. The mineralization is believed to be derived from the hydrothermal products of a carbonatitic differentiate. The deposit, however, was reported abandoned in 1981.

At Mrima Hill, southwest of Mombasa, Kenya, rare earth minerals are concentrated in thick residual soils overlying a deeply weathered carbonatite. The REE are mainly concentrated in earthy cryptocrystalline (Section 12.0) monazite associated with barite, gorceixite, $(\text{Ba}, \text{Al})_3(\text{OH})_7\text{P}_2\text{O}_7$, and pyrochlore. Although production has been contemplated, none currently exists. The deposit is also one of the richest concentrations of niobium in the world but the fine-grained and friable nature of the pyrochlore has prevented development to date.

Monazite has been identified in strontianite-rich carbonatitic dykes and veins at Kangankunde Hill in southern Malawi, and also in the thin residual soil overlying the deposits. Other REE-bearing carbonatites include Wigu Hill in Tanzania and Nkombwa Hill in Zambia. Except for Kangankunde Hill, none of these deposits has been delineated in detail and no production from any of them currently exists.

6.5.2.1.2 Asia

REE are associated with the Bayan Obo iron ore deposits in the Ulangab district of northern China, making the deposits the largest identified in the world to date. The iron ore deposits form tabular bodies and lenses in steeply dipping dolomites; the principal iron ore minerals are magnetite, specularite and hematite, with which rare earth minerals are intercalated. Some of the more important rare earth minerals are the nioboae-schynite-titanaeschynite series $(\text{Ce}, \text{Th})(\text{Nb}, \text{Ti})_2(\text{O}, \text{OH})_6$, bastnaesite and monazite. Emplacement of the alkaline-carbonate and iron-rich solutions from which iron and rare earth-niobium minerals were precipitated, is believed to be genetically related to Hercynian alkaline granite, syenite and gabbroic rocks which crop out adjacent to the deposit. The geochemistry of the deposits suggests a carbonatite association. Since 1974 a REE concentrate has

been recovered and a range of REE products of the cerium sub-group produced. The deposit is the world's largest source of samarium.

6.5.2.1.3 North America

The most important REE-bearing carbonatite in the world is located at Mountain Pass, California. The deposit is mined by MolyCorp Inc., a wholly owned subsidiary of Unocal Corp. and Associated Minerals (USA) Ltd. Inc., a subsidiary of the Australian company, Renison Goldfields Consolidated Ltd. REE mineralization, chiefly as bastnaesite, has developed in carbonatites intruded into a Precambrian basement complex consisting mainly of granite gneiss. Carbonatite is found in narrow veins, mostly less than 2 metres wide, and also comprises a large orebody, the Sulphide Queen, which is 730 metres by 210 metres in size and the centre of current production. The ore contains, on average, 12% bastnaesite, 20% barite, 10% quartz and other silicates, and 60% carbonates (chiefly calcite), and yields a feedstock containing 7% REO.

Rhone-Poulenc has recently acquired the tailings of a former iron ore mine at Mineville, New York. The tailings are rich in europium and yttrium. Production of several hundred tonnes per year of REE's was planned to commence in 1987.

6.5.2.1.4 South America

In Brazil, rare earth minerals are found in three separate deposits, within residual soils overlying the deeply weathered Barrairo do Araxa carbonatite complex near Araxa in Minas Gerais. REE's are associated with earthy monazite and goyazite, $\text{SrAl}_3\text{P}_2\text{O}_7(\text{OH}_7)$. The complex is the world's principal source of niobium and apatite and is being exploited on an

increasing scale; however, there is no production of REE because the ore is difficult to process. REE's and thorium are also closely associated with a large magnetite stockwork cutting alkaline igneous rocks at Morro do Ferro, on the Pocos da Caldas plateau between Minas Gerais and Sao Paulo states. The alkaline rocks, consisting of syenite and phonolite, have been deeply weathered (≈ 100 m) and are locally enriched in REE's (1.5-4.0% REO) and thorium in the vicinity of magnetite veins. REE's are found in allanite, $(\text{Ce,Ca,Y})_2(\text{Al,Fe})_3(\text{SiO}_4)_3\text{OH}$, particularly in its weathering products and also in bastnaesite. Although easily worked, the ore is difficult to process and there is no production.

Preliminary geological studies reportedly delineated economic concentrations of rare earths and niobium at Cerro Impacto, Bolivar State, Venezuela. Intense weathering has leached the original carbonatite source rock to produce thick lateritic beds with enrichment of rare earths (0.1-11.0% REE) and other elements.

6.5.2.2 Placers

Monazite has a high specific gravity and is resistant during weathering and transportation. Placer concentrations therefore develop under favourable conditions, usually in association with other heavy minerals such as ilmenite, zircon and rutile, although cassiterite and gold are known. Monazite-bearing placers have been widely reported in fluvial (Section 12.0), lacustrine (Section 12.0) and deltaic deposits but the most economically important are beach and dune sand deposits. Production is confined primarily to relatively unconsolidated beach deposits of Holocene to Late Tertiary age. The exceptions are the paleo-placers of the Precambrian Blind River Formation in Ontario, from which REE's are extracted as a by-product of uranium mining.

Monazite is the most common rare earth mineral reported in placer deposits, although minor quantities of xenotime are recovered and the multioxide euxenite has been worked, primarily for its niobium content.

6.5.2.2.1 Africa

Minor quantities of monazite were, until 1979, recovered as a by-product from tin placers in the Plateau Province of northern Nigeria. Monazite is also obtained as a by-product from alluvial (Section 12.0) and eluvial (Section 12.0) tin and gold placers in the Kivu region of eastern Zaire. Monazite was formerly produced from the Nile delta, where heavy mineral sands near Rosetta contained 0.5% monazite. Ancient beach and dune deposits on the south-southeastern coast of Madagascar were in production until 1974. Currently, QIT Fer-et-Titane Inc. and the Madagascan government intend to undertake heavy mineral sands production in 1989, primarily for ilmenite. Proposals have been made to develop heavy mineral beach sand deposits containing monazite in Liberia, but no production has occurred to date. Monazite is believed to be obtained as a by-product of ilmenite, zircon and rutile recovery from heavy mineral sands at Richards Bay on South Africa's east coast.

6.5.2.2.2 Asia

The principal beach placer deposits in southern India are in the Manavalakurichi area, Kanniyakumari district, Tamil Nadu and between Neendakara and Kayankulam in the Chavara region of Kerala State. The principal source of monazite in India is the heavy mineral sands at Manavalakurichi, where monazite makes up 5% out of a total heavy mineral content of 80%. In Kerala State beach placers contain 1-2% monazite out of a total

heavy mineral content of 75%. In both cases ilmenite is the major product with lesser amounts of zircon, rutile, garnet and sillimanite. Similar deposits have recently (1984) gone into production at Gapalpur in Orissa State.

Bangladesh intends to extract heavy minerals, including monazite, from the Cox's Bazaar coastal area. In Malaysia at Perak and Selangor significant quantities of monazite and small amounts of xenotime are produced from the heavy mineral residues (mainly ilmenite) of alluvial tin deposits. In Thailand, monazite and xenotime are produced as by-products during the processing of mineral sands for tin. Monazite is an accessory mineral in tin placer deposits in Indonesia and beach placer deposits of potential economic interest are also located on the west coast of Kalimantan and the southwestern coast of Sumatra. Heavy mineral placer deposits of fluvial origin, in which monazite is often the most abundant heavy mineral, are found at several locations in South Korea and littoral deposits are present along the east and west coasts. The source rocks are granite gneiss and granitic rocks which cover about one-half of the country. Commercial recovery of monazite has been confined to stream placers but beach sand deposits also have potential. Monazite with zircon, ilmenite and rutile is reported in beach placer deposits associated with offshore sand bars on the southwestern coast of Taiwan. The largest heavy mineral sand deposit in Sri Lanka is situated on the northeast coast at Pulmoddai and is worked for ilmenite (70-72%), zircon (8-10%), rutile (8%) and monazite (0.3%). Monazite is believed to be recovered as a by-product of alluvial gold mining in the USSR and is also produced from placer deposits in Guangdong and Guangxi provinces, China.

6.5.2.2.3 Australia

In Australia monazite is produced chiefly in Western Australia and to a much more limited extent, on the east coast in Queensland and New South Wales. Environmental legislation has prevented approximately half of the east coast reserves from being exploited.

In Western Australia the heavy mineral sands are worked principally for ilmenite, although rutile, zircon, leucoxene and monazite are important by-products. Mining has been undertaken since 1956 in the Geographe Bay area between Bunbury and Busselton in the southwest and since 1974 at Eneabba, 250 kilometres north of Perth. The Eneabba deposits are the world's major source of monazite. In the southwest, the deposits are located on the Swan Coastal Plain, on or close to shore lines of Pleistocene to Holocene age which now stand variously between sea level and 76 metres above it. Monazite is typically concentrated towards the base of a deposit but comprises less than 1%.

The Eneabba heavy mineral sands were deposited in Late Tertiary or Early Pleistocene times and paleoshorelines are situated up to 50 kilometres inland. The deposit consists of an association of beach, estuarine and dune sands. Modern beach deposits are small in size and of no economic significance, although offshore exploration has been carried out.

The east coast of Australia, for about 2,000 kilometres between the Hawkesbury River north of Sydney in New South Wales and north of Rockhampton in Queensland, is fringed with Holocene to late Pleistocene sand beaches and dunes which extend up to 13 kilometres inland. Natural concentrations of heavy minerals are principally worked for their rutile and zircon contents and monazite constitutes less than 0.8% of the heavy mineral fraction.

6.5.2.2.4 Europe

Reserves of ilmenite, rutile, zircon and possibly monazite in heavy mineral sands at Cuxhaven in the Federal Republic of Germany have been delineated. The fossilized beach sand deposits are apparently similar to those on the east coast of Australia and are of Tertiary age.

6.5.2.2.5 North America

U.S.A. rare earth mineral production from placers originates in the southeast. Monazite has been sporadically recovered from fluvial deposits in Cleveland County, North Carolina and processed for its contained thorium. Monazite has been recovered from beach sand deposits in both Florida and Georgia as a by-product of ilmenite, leucoxene and zircon recovery. Currently, Pleistocene beach sands containing 3-4% heavy minerals are under production at Green Cove Springs, Florida by Associated Minerals (U.S.A.) Ltd. and are the only source of monazite in the USA.

P.W. Gillibrand Co. began production of heavy mineral sands at Soledad, California in 1985. The heavy mineral sands contain 33% ilmenite, 20% magnetite, 27% apatite and 4.5% zircon; the apatite contains 2% yttrium. It is not known whether the yttrium will be extracted.

Mining of rare earth minerals in Canada has been limited to relatively small outputs of by-product residues from uranium mining at Elliot Lake, Ontario. The pyritic matrix of a Precambrian quartz pebble conglomerate, comprising a consolidated paleoplacer (Section 12.0), contains minute grains of uraninite, UO_2 , brannerite, $(U,Ca,Ce)(Ti,Fe)_2O_6$ and monazite. Denison Mines Ltd. produced a yttrium concentrate until 1978

when the process became uneconomic. The uranium ores contain 0.11% uranium oxide, 0.028% thorium oxide and 0.057% rare earth oxide. Denison Mines, SM Yttrium Canada (a joint venture of the Japanese companies Shin-Etsu Chemical and Mitsui & Co.) and Unocal Canada opened a new separation plant at Elliot Lake in 1986 to produce 140 tonnes of yttrium oxide in concentrates. Rio Algom Mines Ltd. recovered thorium and rare earths concentrates as a by-product of its Elliot Lake mining operations but the operation has been suspended. Similar deposits at the Agnew Lake mine, east of Elliot Lake, contain higher concentrations of REE but are not recovered.

6.5.2.2.6 South America

The major Brazilian REE placer deposits are situated on the coast from Rio de Janeiro to Canavieiras in Bahia State. Monazite has been most consistently worked along the coast of the states of Espirito Santo and Rio de Janeiro. The deposits are low grade, are situated in raised terraces, elevated beaches and bars, and are mainly derived from Tertiary sandstones. Monazite is mined for its own value, not as a by-product; ilmenite, rutile and zircon are also extracted from the heavy mineral sands as by-products.

6.5.2.3 Apatite

Apatite in phosphate rock is often enriched in REE, which could be recovered during phosphoric acid manufacture, the major end-use for phosphate rock. Apatites of marine origin, on which world phosphoric acid production is predominantly based, contain between 110 and 1550 ppm REO. Characteristically in sedimentary phosphate rock there is an enrichment in yttrium and a deficiency in cerium, reflecting the composition of sea water.

Apatite deposits with sufficiently high REE contents to be considered as potential commercial sources are found associated with alkaline igneous complexes. By-product recovery of REE's from apatite mined from alkaline igneous rocks for phosphate fertilizer manufacturing is believed to be confined to the Kola Peninsula, U.S.S.R. The production of apatite concentrates from the phoscorite and pyroenite zones of the Palabora complex in South Africa is being considered.

Other potential sources of REE-bearing apatite include magnetite deposits in which apatite is present as a deleterious impurity and must be removed prior to iron and steel making.

6.5.2.4 Veins

Only rarely are non-carbonatitic vein deposits sufficiently enriched in REE's to make them economically attractive. A monazite and apatite-bearing vein at Steenkampskraal in South Africa yielded a 6% thorium-bearing monazite concentrate until mine closure in 1965. Other minerals present included zircon, magnetite, pyrite, chalcopyrite and galena. The deposit was emplaced in an elongated, sub-vertical shear zone which traverses a granite gneiss.

Monazite, together with some bastnaesite, comprise up to 2% of the ore at the Buffalo fluorspar mine near Naboomspruit, South Africa. The fluorspar mineralization is found mainly as simple or composite veins in leptite (Section 12.0), which is present as roof pendants in the Bushveld Granite. The veins have a variable thickness but average about 10 millimetres; fine-grained monazite occurs preferentially along the vein-leptite contact. By-product recovery of a monazite concentrate from tailings is being considered.

A rare earth concentrate was produced as a by-product of galena from the Korsnas mine on the Gulf of Bothnia in Finland. The deposit occupies a vein cutting Precambrian migmatitic mica gneiss. The ore minerals include galena, apatite and monazite, whereas the gangue consists of calcite, feldspar and diopside. Mining ceased in 1972.

6.5.2.5 Pegmatites

Pegmatites may be enriched in REE's and have been mined on a very small scale. Yttrotantalite, $(Y,U,Fe)(Ta,Nb)O_4$ and gadolinite, $(Y,Ce)_2FeBe_2Si_2O_{10}$, totalling a few hundred kilograms, have been recovered from pegmatites at Cooglegong in Western Australia. Bastnaesite has been recovered from pegmatites in Madagascar.

At present, Highwood Resources Ltd. and Hecla Mining Co. are intending to develop a deposit at Thor Lake in the Northwest Territories. Rare earths are found in zoned pegmatites associated with an Archaean alkaline-syenite intrusive complex. The ore grades between 0.66 and 1.4% BeO and 0.21% Y_2O_3 ; bastnaesite is apparently the principal REE mineral.

6.5.2.6 Uranium-bearing Minerals

REE's, mainly contained in the uranium-bearing minerals allanite and stillwellite, were produced from the Mary Kathleen uranium skarns in Queensland, Australia. Uranium mining at Mary Kathleen ceased in 1982.

6.5.2.7 Sedimentary Copper

The Olympic Dam copper deposit in the Roxby Downs area of South Australia contains significant amounts of REE's in the ore zone, mainly as bastnaesite and florencite $\text{CeAl}_3(\text{PO}_4)_2(\text{OH})_6$. The copper-uranium-gold-REE mineralization is both stratabound (Section 12.0) and transgressive (Section 12.0) and is situated within a thick sequence of monomictic and polymictic (Section 12.0), iron-rich sedimentary breccias of Proterozoic age. REE's are associated with copper, and particularly uranium. The deposit, estimated to contain 2×10^9 tonnes of ore grading 1.6% Cu, 0.64 kg/t U_3O_8 and 0.6 g/t Au, is a potentially large source of REE's.

6.5.2.8 Others

Easily worked deposits of REE's have recently been developed in China at Nan-lu in southern Jiangxi province. The precise nature of these deposits is uncertain, but reserves have been placed at 1×10^6 tonnes REO. Available information indicates that the deposit consists of highly weathered phosphate minerals (e.g. apatite and xenotime), resulting in an ore with low cerium content and high samarium, europium, terbium and yttrium content.

Near Lac Brisson on the Quebec-Labrador boundary the Iron Ore Company of Canada has evaluated a deposit (Strange Lake) containing REE's, yttrium, zirconium, columbium and beryllium. In 1984 a decision not to develop the deposit was made due to planned increased REE and yttrium production in Canada and the U.S. by other producers.

6.6 New Brunswick Potential

6.6.1 Occurrences

There are a number of occurrences of rare earth elements, including yttrium, in New Brunswick. These occurrences are usually based upon mineralogical identification or are the result of yttrium analysis. Apatite and monazite are the only two REE-bearing minerals reported to have been identified. Rarely are actual REE analyses available, one exception being the analytical results reported by Warner (1986). Samples from the Zealand Station beryl occurrences yielded less than 500 ppm total REE (excluding promethium and yttrium).

6.6.1.1 Mt. Pleasant (45°27':66°50')

Ruitenbergs (1976) summary of the Mt. Pleasant ore bodies states that they occur in intensely silicified and brecciated banded pyroclastics. Ore minerals have been concentrated mainly in breccia matrix composed of crushed silicified rock, fluorite, kaolinite and chlorite. Three distinct mineral assemblages have been identified, the first and third being REE-bearing:

- 1) wolframite, rutile, cassiterite, rare earth phosphates, zircon, arsenopyrite and lollingite
- 2) arsenopyrite, lollingite, molybdenite, bismuth and bismuthinite
- 3) sphalerite, chalcopyrite, pyrite, pyrrhotite, arsenopyrite, stannite, stannoidite, kesterite, monazite, roquesite, cassiterite, rutile, galena, aikinite, bismuthinite, galenobismutite, cosalite and tennantite

The third assemblage is in part superimposed upon the earlier assemblages but it occurs mainly as discontinuous veins and pods. The highest grade of this material is found in fracture zones and breccia pipes within latite or rhyolite porphyries along the contacts of banded pyroclastic (Section 12.0) dykes. The breccia pipes appear to have developed as a result of explosive hydrothermal activity along major fracture zones. The "mineralizing" fluids contained a wide variety of elements and were rich in fluorine and silica.

The only known polymetallic mineral deposit associated with terrestrial volcanic centres in the Northern Appalachians is at Mt. Pleasant; there are, however, similar deposits associated with fracture zones within and along the contacts of quartz-monzonite intrusions at Eagle Lake and Burnt Hill.

6.6.1.2 Cumberland Hill (46°02':65°50')

Fyffe and Barr (1986) documented the petrographic and chemical characteristics of the Carboniferous volcanic rocks in New Brunswick. Twenty-one representative samples were collected from the several exposures in the province and subjected to petrographic and chemical analyses.

Two samples of the peralkalic (Section 12.0) rhyolite of Late Westphalian age exposed at Cumberland Hill in central New Brunswick yielded high niobium (207-209 ppm), yttrium (164-177 ppm), zirconium (1733-1877 ppm) and gallium (56-57 ppm) contents. Their high trace element values are "indicators of potential economic concentrations of rare earth elements" (Fyffe and Barr, 1986).

6.6.1.3 Lutes Mountain ($46^{\circ}12':64^{\circ}52'$)

Between 1970 and 1972, BP Oil Ltd. (Wilson and Ball, 1983) discovered mineralized red conglomerate float containing 0.3% uranium, 1.0% copper and 0.1% yttrium in the Lutes Mountain area. The float was thought to have been derived from local Mississippian, Memramcook Formation basal conglomerates. Exploration carried out by several firms through the 1970's identified radiometric anomalies in the area but no further reference is made to yttrium. The anomalies were identified through the use of soil and till geochemistry, soil radon and spectrometric surveys and analysis of drill core.

Amrex (1979) conducted uranium exploration in the Scotch Settlement area (northeast of Lutes Mountain), concentrating on the Memramcook and Albert Formation sedimentary rocks. Analyses of bedrock samples yielded 0.3-1.0% TiO_2 , 0.03-0.1% yttrium, 0.003-0.01% zirconium and less than 0.003% combined cerium and lanthanum.

6.6.1.4 Hayesville and Napadogan Map-Areas ($46^{\circ}25':66^{\circ}46'$)

In 1959 and 1960 Poole and Lachance (-) completed analyses of placer pan concentrates collected during bedrock mapping of the Hayesville (NTS 21J/10) and Napadogan (NTS 21J/7) map-areas. Four of the samples yielded anomalous yttrium contents, and three of these were collected in the same general area, in the northwest corner of the Hayesville map sheet. That area is underlain by cataclastic (Section 12.0) and migmatitic (Section 12.0) granitic to dioritic rocks. Yttrium and zirconium distribution parallel one another, and most "higher-than-normal" values appear in concentrates draining granitic rocks of all ages, apparently reflecting the accessory mineral assemblages. A single concentrate containing anomalous zirconium and yttrium

originated from an area underlain by Silurian greywacke in the centre of the Napadogan map-sheet; no explanation for this anomaly is available.

6.6.1.5 Lake Utopia ($45^{\circ}10':66^{\circ}50'$)

Reconnaissance uranium exploration completed in the Lake Utopia area (Jenkins and Madan, 1979) yielded anomalous rare earth element analyses. A sample (9CJ-B10.5) taken from the Silurian-Devonian basic volcanics and related intrusives at the southwest contact of the Saint George Batholith contained 0.1-0.3% yttrium, 3.0-10.0% zirconium, 0.03-0.1% lanthanum and 0.1-0.3% cerium.

Van Wagoner et al. (1987) have mapped Devonian interbedded rhyolitic and basaltic flows and pyroclastic rocks, and red and green-grey shale and sandstone in the area.

6.6.1.6 Manners Sutton ($45^{\circ}44':67^{\circ}05'$)

The Manners Sutton area, in the vicinity of Harvey Station, has been the site of recurrent uranium exploration (Wilson and Ball, 1983). The Harvey Formation felsic volcanics underlie the area, unconformably overlying Silurian metasedimentary rocks, and covered by Mississippian and Pennsylvanian clastic sedimentary rocks. The Manners Sutton showing consists of several fractured linear zones containing veins of pitchblende accompanied by pyrite, fluorite, arsenopyrite and intense alteration of the surrounding thinly banded rhyolite.

One drill core sample (Beaudin et al., 1980) consisting of "clay" (altered felsic extrusives), yielded approximately 3% uranium oxide and 0.1 to 0.3% yttrium.

6.6.1.7 Long Lake (47°03':66°50')

Cambro-Ordovician metasediments are in contact with Devonian quartz-monzonite intrusive rocks in the Long Lake area (Boutcher et al., 1981). Petrographic analyses indicate the presence of accessory rutile, zircon and apatite in the intrusion. One sample returned an yttrium analysis of 0.01-0.1%.

6.6.1.8 McDonald Brook (46°34':66°58')

In the McDonald Brook area, a sequence of Cambro-Ordovician quartzite and paragneiss is intruded by Ordovician and mineralogically specialized (Burnthill-type) Devonian granites which have been the focus of tin-tungsten exploration in west central New Brunswick (Bucknell, 1982). Petrographic analyses of bedrock samples indicates the presence of accessory rutile, fluorite and apatite. Two yttrium analyses returned results of 0.01 to 0.1%.

6.6.1.9 Benjamin River (47°55':66°13')

In the vicinity of the South Branch of the Benjamin River, southwest of the Village of Benjamin River on the Bay of Chaleur, an occurrence of diopside-magnetite-fluorite-apatite is reported (Marleau, 1969; Crocco, 1977; and Chandra and Irrinki, 1977). The occurrence is associated with a light grey, coarse-grained gabbro which intrudes mafic volcanic rocks. The gabbro contains 60% plagioclase (An₅₅), 25% pyroxene, 5% biotite, 5% chlorite, 5% magnetite and minor apatite (Chandra and Irrinki, 1977). This property is currently held under mineral claim and is apparently being evaluated.

6.6.1.10 Sheba ($45^{\circ}52':65^{\circ}42'$)

Based on known copper, nickel and silver showings near Sheba, approximately 2 kilometres west of Longs Creek, Maritime Resource Research Ltd. conducted on EM-16 survey and diamond drilling program (Prince and Roberts, 1987). Scanning electron microscopy indicated the presence of yttrium phosphate and apatite as minor phases present in one sample of drill core. The property straddles the contact of the Kingston Uplift with the Pennsylvanian cover of the New Brunswick Platform. Drilling intersected dacite tuff and intercalated metasedimentary rocks.

6.6.1.11 Gibson Granodiorite ($46^{\circ}05':67^{\circ}32'$)

The Gibson Granodiorite is exposed south of Upper Northampton, on the St. John River south of Woodstock. Venugopal (1981) describes accessory zircon and apatite in the rock, which varies from a light pinkish grey, equigranular to subporphyritic granodiorite, to a grey quartz diorite. It is composed of plagioclase (50-60%), hornblende (5-10%), quartz (7-15%), chlorite (5-7%), epidote (2-7%), opaques (1-2%), prehnite (1-2%), carbonate (1-2%) and accessory zircon and apatite.

Lockhart and Tays (1971) report accessory zircon and apatite noted during porphyry copper exploration within the pluton. Petrographic analysis of thirty-two samples was completed by the New Brunswick Research and Productivity Council.

6.6.1.12 Hawkshaw Granite ($46^{\circ}05':67^{\circ}48'$)

The Hawkshaw Granite comprises the largest portion of the Pokiok Batholith, which underlies an area extending

from the Chiputneticook Lakes on the Maine-New Brunswick border to Zealand Station and Napadogan in central N.B. Both Lutes (1979) and Venugopal (1981) report apatite as an accessory mineral in the Hawkshaw Granite within their respective map-areas. The granite was mapped on the eastern quarter of the Canterbury-Skiff Lake map-area (H-23) (Lutes, 1979), and in the extreme southeast corner of the Nortondale map-area (I-20) (Venugopal, 1981). Chlorite, muscovite, epidote, sphene, apatite, zircon and opaques were reported to comprise less than 1% of the rock samples examined.

The granite is medium to coarse-grained, light pink, and equigranular to subporphyritic. Alkali feldspar as phenocrysts (Section 12.0) comprises 15-25% of the rock, plagioclase feldspar approximately 40-50%, quartz approximately 25%, and biotite approximately 1%, with the accessory minerals making up the balance (<1%).

Warner (1986) reports varying amounts of fine-grained apatite in both a medium to coarse-grained pink granitic phase and a coarse-grained granodioritic phase of the Hawkshaw Granite. This occurrence coincides with the Zealand Station beryl occurrence.

6.6.1.13 Skiff Lake Granite (45°49':67°32')

The Skiff Lake Granite occupies the westernmost portion of the Pokiok Batholith. Lutes (1979) reports apatite as an accessory mineral in the granite in the Fosterville-North and Eel Lakes (G-23) and Canterbury-Skiff Lake (H-23) map-areas.

The rock is a grey, hiatal (Section 12.0) to seriate (Section 12.0) muscovite-biotite granite. Plagioclase and microcline are present as phenocryst and in the groundmass. Approximately equal proportions of microcline and plagioclase make-up 50%

of the rock. Quartz comprises 35%, biotite 12%, muscovite 1-2% and accessories including zircon and apatite, approximately 1%.

6.6.1.14 Welsford Complex (45°27':66°15')

Payette and Martin (1988) presented information on the petrography, mineralogy and geochemistry of the Welsford complex, an elongate northeasterly trending appendage of the St. George Batholith. The granite is peralkaline and locally enriched in zirconium, niobium, yttrium and rubidium. A yttrium phosphate (britholite-like) mineral of the apatite family was identified as an accessory mineral in the alkali granite (DWfag) of the complex. Bulk-rock compositional data suggests that REE concentrations do not surpass 100 ppm.

6.6.2 Areas of Potential

Evaluation of the REE occurrences listed in Section 6.6.1, combined with the mineralogical and geological information detailing the various REE orebodies compiled in Section 6.5, has led to the singling out of several occurrences as being worthy of additional attention. It has also resulted in the delineation of additional areas and/or rock units which warrant evaluation. These additional areas and/or rock units are not listed as occurrences as there is no analytical or mineralogical data available for them. On the other hand, the process of evaluation resulted in the deletion of several of the occurrences from further consideration.

6.6.2.1 Mt. Pleasant

The presence of REE at Mt. Pleasant suggests that

should consideration be given to reopening the mine, recovery of the REE could be a factor. In order to assess that possibility, questions of REE mode of occurrence, grade and metallurgy must be addressed. Whether these questions have or have not already been addressed by the current owners of the property was not determined, but remains for those who pursue the recommendations of this study.

Ruitenbergs (1976) identification of Burnthill and Eagle Lake as being occurrences similar to Mt. Pleasant suggests that their REE content be assessed.

6.6.2.2 Geochemical Occurrences

The occurrences at Lutes Mountain, in the Hayesville and Napadogan area, at Lake Utopia and at Manners Sutton are designated on the basis of a limited number of anomalous litho-geochemical values. Little or no geological data, including mineralogical data, is available. This lack of data makes it impossible to determine whether or not these occurrences offer any potential. The details of the mineralogical association of the occurrences and a detailed knowledge of the geology of the host rock units is required.

6.6.2.3 Apatite Occurrences

The apatite occurrences at Long Lake, McDonald Brook, the Gibson Granodiorite, the Hawkshaw Granite, the Skiff Lake Granite and the Welsford Complex all appear to be in the form of accessory mineralization. Although the Long Lake and McDonald Brook occurrences yielded between 0.01 and 0.1% yttrium, apatite mineralization is present in only accessory amounts. Lutes (1987) states that none of the granite phases comprising the

Pokiok Batholith (e.g., the Hawkshaw Granite and Skiff Lake Granite) can be categorized as so-called A-type granites, that is, alkaline and containing higher quantities of REE and yttrium.

The Sheba occurrence appears minor, although given the availability of drill core and/or outcrop samples, the occurrence warrants at least cursory examination in order to determine its significance and potential.

The Benjamin River occurrence appears, at this time, to be the premiere REE occurrence in the province. The geological and mineralogical associations represented by this occurrence suggest a model upon which to base additional exploration. Additional detailed information concerning these associations would aid in more fully developing the model, thus optimizing its utilization for the delineation and study of additional occurrences.

6.6.2.4 Becaguimec Lake Gabbro and Others

St. Peter (1982) described the Devonian Becaguimec Lake Gabbro ($46^{\circ}20':67^{\circ}12'$) in west-central New Brunswick as the largest mafic pluton in the province. The pluton consists of gabbro with minor associated gabbro pegmatite and granodiorite veins. The gabbro is mottled dark green to dark grey and white, medium to coarse-grained, and typically subophitic (Section 12.0). Mineralogically, the gabbro consists of abundant plagioclase, lesser clinopyroxene, minor disseminated opaques and accessory apatite and sphene. Lutes (1981) identified abundant magnetite in the gabbro and noted the pronounced aeromagnetic expression associated with the unit. Unconfirmed accounts suggest that zones enriched in apatite and magnetite may exist in the general vicinity of Owl Lake ($46^{\circ}19':67^{\circ}12'$), in the southeast corner of the North Branch Becaguimec-Carlisle-Cloverdale map area (I-18).

It is possible that the Becaguimec Lake Gabbro may host occurrences of apatite similar to that reported in the Devonian gabbro at Benjamin River. Mafic intrusive rocks mapped by Davies (1977) at Eel Bay ($48^{\circ}22':66^{\circ}21'$), Eel River ($48^{\circ}01':66^{\circ}22'$), Blue Mountain ($47^{\circ}35':66^{\circ}15'$), Jacquet River ($47^{\circ}53':66^{\circ}03'$) and Antinouri Lake ($47^{\circ}50':66^{\circ}00'$), plus several other slightly older Devonian gabbros in the Chaleur Bay Synclorium (Ruitenberg, *et al.*, 1977) should also be considered as possibly fitting the model. Fyffe (1982) delineated several gabbroic intrusions, equivalent in age to the Becaguimec Lake Gabbro which should be similarly considered. They are located at Gulquac Lake ($46^{\circ}57':66^{\circ}56'$), Beadle Lake ($46^{\circ}47':67^{\circ}20'$), Northeast Clearwater Brook ($46^{\circ}50':66^{\circ}40'$), North Dungarvon River ($46^{\circ}54':66^{\circ}40'$), Otter Slide Mountain ($46^{\circ}28':66^{\circ}55'$), at the south contact of the Burnthill intrusion, just south of Juniper and at Ayers Lake ($46^{\circ}12':67^{\circ}20'$).

6.7 Processing

The mining and processing techniques used in the extraction of rare earth minerals depend on the physical and chemical characteristics of the ore deposit. Thus the exploitation and beneficiation of loosely consolidated heavy-mineral-bearing sands are very different from those used for primary bastnaesite deposits.

The heavy minerals, including the heavy rare earth minerals, are recovered from placers by dredges, shaking tables, jigs and Humphreys spirals. The bulk concentrate of heavy sands usually consists mainly of titanium and zirconium minerals with from 1 to 20% monazite. Monazite is separated from other components by combinations of gravity, electromagnetic, and electrostatic methods. Flotation has been used for Indian monazite separation and for the vein monazite ore from South Africa.

A froth flotation technique uses sodium silicate as a conditioner and sodium or potassium permanganate to improve monazite flotability.

Industrial processing of monazite concentrates consists initially of digestion in sulfuric acid or caustic soda, subsequent separation of the thorium and certain other elements, and finally recovery of rare earth compounds as a group in a pure state.

In the acid process, finely ground concentrate is mixed with concentrated sulfuric acid in externally heated cast iron pots. After roasting under controlled conditions of concentration and temperature, the thorium and rare earth elements are dissolved in water as sulfates. The insoluble impurities are separated by filtration. The thorium is precipitated from the solution, and the rare earth elements subsequently are precipitated as an insoluble double sulfate salt by reacting with a sodium sulfate solution or as the rare earth oxalate with oxalic acid. The double salt can be reacted with sodium hydroxide, followed by treatment with hydrochloric acid to form the chloride.

In the alkaline process, the monazite concentrate is finely ground and reacted with a hot concentrated solution of caustic soda. In the reaction, the hydroxides of the rare earth elements and thorium are left undissolved, and trisodium phosphate remains in solution to be recovered by crystallization from the filtrate. The hydroxides are washed, dissolved in hydrochloric acid, and subjected to partial neutralization to allow separation of crude thorium hydroxide from a filtrate containing rare earth chlorides. The rare earth chlorides can be recovered by evaporation and the hydroxides reprecipitated, or the solution may pass directly to ion-exchange separation of the individual rare earth elements. This method is simple, permits separation of pure mixed rare earth concentrate early

in the process, and makes marketable trisodium phosphate as a by-product. However, the reagent cost is higher than that for the acid process, and the process is not amenable to low-grade ores.

California bastnaesite is mined by open pit methods. The ore is upgraded from 7% REO to a concentrate containing more than 60% REO using hot froth flotation techniques. Calcite is removed from the concentrate by leaching with 10% hydrochloric acid and countercurrent decantation. The bastnaesite is not dissolved by this treatment, and the concentrate is upgraded to 72% REO. Finally the leached concentrate can be roasted to remove the CO_2 of the bastnaesite, resulting in a product with over 90% REO. The 90% REO calcine is leached with hydrochloric acid for conversion to soluble rare earth chlorides. Undissolved cerium is passed through a countercurrent decantation and thickening circuit and then filtered, resulting in a filter cake composed of about 70% REO, more than 90% of which is cerium oxide. This precipitate is reprocessed, dried, and sold as a cerium concentrate. The rare earth elements in the thickener overflow (about 100 grams REO per litre) are separated by solvent extraction methods (liquid-liquid ion exchange) into various mixed rare earth concentrates or into individual elements.

Plants in the U.S.S.R. and in Poland recover RFO from apatite during production of phosphoric acid and fertilizer. The process includes decomposition with concentrated nitric acid, salting-out of silicic and fluorosilicic acids with sodium nitrate, filtering, precipitation of the rare earth phosphates from the filtrate by partial neutralization with ammonia, dissolution of the rare earth concentrate in nitric acid, and final purification by oxalate precipitation.

Many commercial rare earth salts contain individual elements in about the same ratio as in the ore treated. Solvent

extraction and ion exchange are the commercial methods used for the separation of rare earth elements. One or both techniques are used by most companies that produce rare earth compounds. Other methods of rare earth separation are fractional crystallization by evaporation and thermal reactions, which include fusion and volatilization.

The most common method for preparing cerium metal and mischmetal is by the electrolysis of fused anhydrous rare earth chloride at about 900°C , using iron pots as cathodes and graphite rods as anodes. Molten metal accumulates at the bottom of the pot. Other electrolytic methods that have been employed include electrolysis of oxides and fluorides in mixed molten fluoride baths; electrolysis of oxides and fluorides in mixed fluoride-chloride baths; electrolysis from molten electrolytes into low-melting-point metals such as zinc and cadmium; and aqueous electrolysis into mercury cathodes.

Metallothermic reduction of rare earth compounds, using lithium, sodium, potassium and magnesium is used to obtain the metals. Samarium, europium and ytterbium metals can be prepared by reducing their oxides with other rare earth elements, zirconium or mischmetal. Purification of rare earth metals has been accomplished chiefly by distillation and solid-state electrolysis.

7.0 Titanium

7.1 Properties

Titanium metal has an atomic number of 22 and an atomic weight of 47.9. The metal's melting point is 1670°C and the specific gravity is 4.51. Titanium has two outstanding properties, its high strength-to-weight ratio and its exceptional corrosion resistance. In its oxide form titanium dioxide is widely used as a white coloured pigment in a wide variety of products.

7.2 Saleable Forms and Price

The main forms in which titanium is used commercially are titanium dioxide, titanium metal and alloys. Trade in titanium is conducted in three basic forms, mineral concentrates, metal and pigment.

Prices for these various forms of titanium were published by the American Metal Market to cover 1985 prices.

Concentrates:

ilmenite, f.o.b. eastern U.S. ports (1984 price)	\$US70-75/tonne
ilmenite, f.o.b. Australian ports	\$US38-42/tonne
ilmenite, large bulk lots, f.o.b. U.S. eastern ports	\$US50-56/tonne
rutile, f.o.b. eastern U.S. ports (1984 price)	\$US460-490/ton
rutile, bagged, f.o.b. Australian ports	\$US371-386/ton
rutile, bulk, f.o.b. Australian ports	\$US315-328/ton
rutile, large bulk lots, f.o.b., f.o.b. U.S. eastern ports	\$US350-360/ton
synthetic rutile, f.o.b. Mobile, AL.	\$US350/ton

titanium slag, 80% TiO ₂ , f.o.b. Sorel, Que.	\$US196/tonne
titanium slag, 85% TiO ₂ , f.o.b. Richards Bay, S.Af.	\$US212/tonne

Metal:

sponge	\$US3.50-4.00/pound
mill products:	
bar	\$US9.77/pound
billet	\$US8.35/pound
plate	\$US10.64/pound
sheet	\$US12.73/pound
strip	\$US13.45/pound

Pigment:

titanium dioxide, f.o.b. U.S. plants, anatase	\$US0.72-0.73/pound
titanium dioxide, f.o.b. U.S. plants, rutile	\$US0.78/pound

7.3 Production Statistics

concentrate type and country	1981	1982	1983	1984	1985 ^e	1986 ^e
	(tonnes)					
Ilmenite ¹ and Leucoxene ¹						
Australia:						
ilmenite	1,325,236	1,152,777	898,989	1,146,804	1,255,800	
leucoxene	19,321	19,800	13,400	15,933	17,290	1,550,000
Brazil ^e	15,905	11,357	30,547	41,072	45,500	55,000
China ^e	136,500	136,500	140,140	140,140	140,140	na
Finland	162,000	168,321	164,409	167,440	136,500	na
India	163,018	153,412	134,892	140,434	170,170	170,000
Malaysia	173,293	101,516	223,413	235,713	275,730	180,000
Norway	661,650	553,475	557,612	663,415	737,555	na
Portugal	401	587	271	175	146	na
Sri Lanka	80,259	88,494	82,032	102,365	100,100	150,000
Thailand	37	18	206	538	500	na
U.S.S.R. ^e	427,700	432,250	436,800	441,350	445,900	na
U.S.A. ²	493,545	239,686	w	w (> '82)	w	265,000
Total	3,658,867	3,038,193	2,682,771	3,095,368	3,325,331	

Rutile:

Australia	231,533	221,382	158,708	182,044	204,750	250,000
Brazil	173	235	464	413	455	na
India	6,731	5,800	5,551	6,006	7,007	na
Serra Leone ³	50,953	47,856	72,023	91,583	80,990	100,000
South Africa ^e	50,050	47,320	56,420	56,420	55,510	55,000
Sri Lanka ^e	37,912	7,235	8,118	6,487	7,007	na
U.S.S.R. ^e	10,010	10,010	10,010	10,010	10,010	na
U.S.A. (22,750 tonne capacity)	w	w	w	w	w	27,000
Total	362,792	339,839	311,293	352,964	365,729	

Anatase, unbene-
ficiated ore⁴

Brazil	2,919,448	2,853,809	2,375,125	2,678,620	2,730,000
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Titaniferous slag¹

Canada ⁵	761,546	671,075	637,000	728,000	846,300
South Africa ^{e6}	371,280	382,200	418,600	418,600	436,800
Total	1,132,826	1,053,275	1,055,600	1,146,600	1,283,100

w - withheld

e - estimated

1 - ilmenite is also produced in Canada and S. Africa but this output is not included here because an estimated 90% of it is duplicative of output reported under "titaniferous slag" and the rest is used for purposes other than production of titanium commodities, principally as steel furnace flux and heavy aggregate

2 - includes a mixed product containing ilmenite, leucoxene, and rutile

3 - contains 96% TiO₂

4 - contains 20% TiO₂

5 - contains 72% TiO₂ in 1981-82, 74% TiO₂ in 1981-82, 74% TiO₂ in 1983 and 80% TiO₂ in 1984-85

6 - contains 85% TiO₂

7.4 Uses

7.4.1 Applications

In terms of tonnage, titanium metal production is twenty times smaller than that of the oxide. In the U.S.A., pigment manufacture accounts for in excess of 90% of titanium consumption.

The largest market for titanium dioxide pigment is

for use in surface coatings, where it imparts whiteness, opacity and brightness to paints and where its refractive index makes it suitable for use in varnishes and lacquers.

The second largest market for titanium pigment is for use in paper coatings or as paper fillers to improve opacity, brightness, and printability. Titanium dioxide is used in photographic papers, in paper boxes which require a light-coloured, high-gloss coating, and in practically all printing paper except newsprint.

The third largest market for titanium pigment is in the plastics industry, where its resistance to degradation by ultraviolet light, high refractive index, whiteness, and chemical inertness to most plastic materials find wide application in many products made of polyethylene, polyvinyl chloride, polystyrene, and polyolefin-type plastics.

Titanium dioxide pigment and other titanium compounds are used in a wide variety of miscellaneous applications, including rubber tires, floor coverings, printing ink, porcelain enamels, wall coverings, oilcloth and other coated fabrics, and roof coatings. Several thousand tons of titanium dioxide are used annually in producing welding-rod coatings, glass fibers, ceramic capacitors, and electromechanical transducers. Commercial carbide cutting tools contain 8 to 85% titanium carbide with or without tungsten carbide in a matrix of molybdenum, nickel, or cobalt. Organotitanium compounds are used as catalysts for various polymerization processes, as water repellants, and in dyeing processes.

Over 80% of the titanium metal consumed in the United States is for transportation equipment in aerospace applications, including aircraft and guided missile assemblies, spacecraft, and turbine engines for aircraft. The remainder is used in

the chemical and electrochemical processing industry, in power plants, and in marine and ordnance applications.

7.4.2 Alternatives

In the specialty applications for metallic titanium in the aerospace industry, there is virtually no metal substitute although aluminum-lithium alloys may offer some potential for aircraft skins. Zirconium can be employed for corrosion resistance in steel and some aluminum alloys.

Tungsten carbide competes with titanium carbide as a cutting surface in machine tools. Synthetic rutile made from ilmenite can be substituted for natural rutile.

Titanium dioxide's position as a pigment does not appear to be equalled by any other material.

7.5 World Deposits

7.5.1 Titanium Mineralogy

Titanium is a major constituent in approximately twenty minerals. Titanium minerals of consequence include anatase, TiO_2 , ilmenite, FeTiO_3 , perovskite, CaTiO_3 , rutile, TiO_2 , sphene, CaTiSiO_5 and leucoxene. The minerals of commercial interest are ilmenite, leucoxene, rutile and anatase. Perovskite could become the base for commercial titanium production given delineation of suitably sized deposits and the commercialization of an appropriate processing technology.

Anatase is the low-temperature polymorph of TiO_2 ; rutile is the high-temperature polymorph. Anatase, as well

as being found as a minor constituent of igneous and metamorphic rocks and in veins and druses within granite pegmatites, is also an alteration product of other titanium-bearing minerals such as sphene and ilmenite. It is a common detrital mineral in sediments, where it is often the result of alteration of ilmenite. Leucoxene is also an alteration product, formed by the leaching of a portion of the iron in ilmenite; it has no specific composition, but is an impure, finely crystalline form of titanium oxide.

Titaniferous magnetite, that is, mixtures of titanomagnetite, ilmenite-hematite and intermediate solid-solution series minerals, may be considered for production of titanium.

7.5.2 Deposit Classification

Production historically has been based on three types of deposits: beach and stream placers, primary deposits consisting of massive titaniferous iron ores, and igneous complexes in which rutile is found in association with anorthosites and similar rocks.

7.5.2.1 Placers

Beach and stream placers commonly contain both rutile and ilmenite associated with magnetite, monazite, zircon, garnet, staurolite, sillimanite, chromite and occasionally radioactive minerals and gold. The heavier minerals are sorted by moving water and are concentrated in the placer deposit.

Ilmenite, as its iron content decreases, passes through stages: "patchy" ilmenite, amorphous iron-titanium oxide and leucoxene. As a result, ilmenite may vary widely in grade from

its theoretical TiO_2 content of 52.8%, to 70% in its most weathered form.

7.5.2.1.1 Africa

The African continent apparently holds considerable untapped potential in both placers and bedrock titanium deposits. The most important of these undeveloped placers are located in Malawi but others are known in Gambia, Ghana, Sierra Leone, Namibia and Madagascar.

African production of placer deposits is based in Sierra Leone and South Africa. Rutile and ilmenite are associated with the diamond deposits of Sierra Leone. Rutile-bearing quartzite and lenticular bands of ilmenite and titaniferous magnetite in the basic igneous complex of the Colony Peninsula are the source of beach deposits of rutile and ilmenite. More than 1.4 million tonnes of rutile have been proven in Lanti Valley sandy grey clay, derived from weathered gneiss. Sierra Rutile Ltd., the sole producer, makes Sierra Leone the world's second largest producer of natural rutile.

Richards Bay Minerals, co-owned by Union Corp. Ltd. (S. Africa) and QIT-Fer et Titane (Canada), produces rutile and titaniferous magnetite from its heavy mineral mining operations at Richards Bay, South Africa.

QIT-Fer et Titane and the Madagascan government intend to develop production of heavy mineral sands in Madagascar by 1989. Initially, ilmenite will be produced but monazite may also be extracted.

7.5.2.1.2 Asia

Titanium mining in Asia, based upon placer deposits, is carried out in India, Japan, Malaysia, Sri Lanka, and Thailand. The details of production in the U.S.S.R. and China are not readily available but the U.S.S.R. at least is known to have placer based titanium mining.

Indian beach sands yield ilmenite at Travancore and Quilon in the state of Kerala. At Travancore, beach sands contain 50 to 70% ilmenite, monazite, zircon, garnet, rutile and silliminite. The sands are derived by weathering of the gneisses and pegmatites of the southern part of the state of Kerala. Mining operations by Indian Rare Earths Ltd. was scheduled to begin in 1985 at the Orissa Sands Complex, from which ilmenite, silliminite, rutile, monazite and zircon are to be extracted.

Beaches on Honshu, Japan contain 9 billion tonnes of black, heavy mineral sands containing 20-30% iron, 8-12% TiO_2 and 0.6% V_2O_5 . These sands are the basis of the Japanese titanium industry.

Ilmenite is associated with cassiterite in parts of the placer tin deposits of Malaysia. Production of ilmenite concentrate from tin-bearing gravels takes place in the states of Perak and Selangor.

Ilmenite, rutile, zircon and monazite are the chief constituents of the black beach sands of Sri Lanka. The most important of these deposits is at Pulmoddai on the east coast. The Pulmoddai sands contain approximately 75% ilmenite, whereas the remaining 25% consists chiefly of rutile and zircon with minor amounts of garnet, spinel, magnetite and quartz. Smaller deposits of black sands are also located on the west coast, at Dundra on the south coast and at Beruwala and Induruwa on

the southwest coast. The Induruwa sands contain appreciable amounts of monazite.

The production of ilmenite concentrate in Thailand is very small and based on mineral sands production.

7.5.2.1.3 Australia

Australia is the world's leading producer of titanium minerals. Strong demand for ilmenite, rutile, monazite and zircon prompted the Australian mineral sands industry to expand production beyond 1984 levels. Mineral Deposits Ltd., TiO_2 Corp., Western Sands Ltd. and Associated Minerals Consolidated Ltd. all planned expansions to come on line between 1986 and 1988.

Beach sands containing ilmenite, zircon and large amounts of rutile are situated on the east coast of Australia, whereas those on the west coast contain less rutile. Most of the production has come from beaches in southern Queensland, northern New South Wales and southwest Western Australia. In Queensland, the beaches near the New South Wales border between North Stradbroke and Tugan Beach contain rutile, zircon and ilmenite. Beach sands on the east coast of New South Wales carry disseminated rutile and ilmenite, which in places have been concentrated into flat seams along the present beaches. The best deposits are in the northern part, from Port Kembla northward to the Queensland border. Ilmenite predominates in the beach sands of southwest Western Australia, with rutile and zircon content generally less than 5 and 10%, respectively. The most important deposits are in the Bunbury-Capel district about 160 kilometres south of Perth. Deposits at Cooljarloo and Jurien Bay north of Perth are to be put into production by TiO_2 Corp. in 1988. Allied Eneabba Ltd., a producer of ilmenite

and zircon in Western Australia, was originally 50% owned by I.E. du Pont de Nemeurs, but has been acquired by Renison Goldfields Consolidated Ltd., Australia's largest producer of ilmenite. AMC has mining and processing operations in the Eneabba and Perth areas.

7.5.2.1.4 Europe

Placer titanium deposits are reported in Portugal, Italy, Spain, Sweden, Switzerland, Yugoslavia and Czechoslovakia. Portugal's production from ilmenite sands in the Castelo Branco district is small. None of the other European countries listed as having placer deposits, report any placer production.

7.5.2.1.5 North America

Placer deposits of ilmenite and rutile are worked in the United States. One paleoplacer is reported in Alberta, Canada, but no production is recorded nor apparently contemplated.

United States producers of placer ilmenite are Associated Minerals (USA) Ltd. Inc. (AMU) at Green Cove Springs, Florida, and E.I. du Pont de Nemours and Co. Inc. at Starke and Highland, Florida. AMU was the only producer of natural rutile concentrate. These deposits contain ilmenite, rutile and zircon. The ilmenite, which is classed as leucoxene, contains extremely fine-grained rutile. The original source area is thought to have been the Piedmont area of Georgia and the Carolinas.

P.W. Gillibrand Co. began production of heavy mineral sands at Soledad, California in 1985. The heavy mineral sands contain 33% ilmenite, 20% magnetite, 27% apatite and 4.5% zircon.

7.5.2.1.6 South America

The main titaniferous deposits of South America are ilmenite and rutile-bearing beach placers in Brazil and Argentina. Similar deposits are reported in Guyana, Guatemala and Mexico. The bauxite ores of Guyana and Brazil also carry considerable titanium, which apparently is lost in the tailings of bauxite processing. At present only Brazil produces any titanium minerals.

Large beach deposits of ilmenite, mixed with monazite, zircon, garnet and quartz sand are situated on the southeast coast of Brazil. The principal beaches are located at Guarapary and Boa Vista in the state of Espirito Santo, near Pronto in the state of Bahia and south of Barrodo Itabapoana in the state of Rio de Janeiro. In places the sands carry as much as 43.6% TiO_2 . The heavy minerals are thought to have been derived from erosion of Archaean granites, gneisses and charnockites. Brazil's rutile and anatase resources are in the states of Goias and Minas Gerais. E.I. du Pont de Nemours and Co. Inc. were considering (as of 1984) a joint venture with the federally owned Cia. Vale do Rio Doce (CVRD) to produce and process anatase in the State of Minas Gerais. CVRD had begun producing anatase concentrate in 1983. International Minerals and Chemical Corp. and the Goias State government through Metais de Goias S.A. intend (1986) to produce and process anatase under a 25 year agreement.

7.5.2.2 Primary

Primary deposits of titaniferous iron ores are known in several countries. Their relative commercial value depends on their titanium content and the liberation size of the titanium mineral. Liberation size is a function of the relative quantities of ferric oxide, ferrous oxide and titanium dioxide present; ilmenite is present as a discrete mineral only if titanium

levels exceed the point at which Ti becomes saturated in magnetite.

Rutile and ilmenite are also associated with anorthosites and associated rocks in basic igneous complexes. However, while there has been production from such deposits, they are generally uneconomic.

7.5.2.2.1 Asia

Little is known of the primary titanium deposits in the U.S.S.R. and China. Ilmenite and titaniferous magnetite are known to be present in the Ural Mountains of the U.S.S.R. and sphene is reportedly being recovered for titanium production. China's production sources are uncertain but it has been reported that a vacuum ore melting furnace for the manufacture of titanium ingots was contracted for in 1984. This installation apparently would bring production of titanium metal to 1200 tonnes per year. No other production from primary deposits exists in Asia.

7.5.2.2.2 Europe

The main titanium resources of the U.S.S.R. are in the titaniferous magnetites in the Ilmen Mountains, the Kussinsk area, the Khibine area of the Kola Peninsula and the Gatskavo region of the Ukraine.

Norwegian titanium deposits associated with norite and anorthosite intrusions in the Egersund region have been mined for ilmenite for two centuries. A deposit at Tellnes in the Egersund-Storgangen region was opened in 1957 by the National Lead Company. The deposit yields ilmenite and magnetite concentrate from an anorthosite intrusion. Aplite veins in deposits at Kragero carry 10 to 15% rutile from which a concentrate containing 97% TiO_2 , and unusually high proportions of chromium

and vanadium are obtained. Productive zones form streaks or stripes within a foliated granite that is flanked by an enormous granite-pegmatite dyke on one side, and by an olivine-hyperite dyke intruding amphibolite on the other.

Finnish production of titanium ore ceased in 1985 with the closure due to high operating costs of the Otanmaki underground mine, operated by Rautaruukki Oy. The mine produced ilmenite, magnetite, pyrite and vanadium pentoxide.

7.5.2.2.3 North America

North America hosts many titaniferous deposits. QIT-Fer et Titane Inc., the only company that mines titanium ore in Canada, produces ilmenite at Lake Allard, north of Havre St. Pierre, Quebec. The deposit is an anorthosite-hosted body of ilmenite which yields ore containing 35% TiO_2 and 40% Fe. U.S. production of titanium ore derives entirely from placer deposits; no primary deposits are currently in production. Large primary deposits of titaniferous ores exist in the Adirondack Mountains of New York where they were developed by the National Lead Company, but were closed in 1984 by NL Industries Inc. The deposits consist of large bodies of ilmenite-magnetite hosted by dark anorthosite, gabbro or norite. Generally where there is ore there is also some gabbro. The ore is a titaniferous magnetite-ilmenite intergrowth that has the textural characteristics of an igneous rock. The ore produced from these deposits contained a minimum of 45% TiO_2 .

7.6 New Brunswick Potential

7.6.1 Occurrences

7.6.1.1 Taylor Village ($45^{\circ}56':64^{\circ}33'$)

Hudgins (1971) reported paleoplacer anatase in conglomerates of the basal Hopewell Group near Taylor Village, southeast of the City of Moncton. He attributed the mineralization to the alteration of pre-existing ilmenite or titaniferous magnetite which were present as fragments or pebbles within conglomerates occupying paleochannels. These coarse clastics are readily attributable to either the Caledonia and/or Westmorland Uplifts.

Preliminary investigations indicate that the conglomerates contain between 2 to 20% anatase-hematite pebbles, which yield between 50-60% TiO_2 and 28-40% Fe_2O_3 . Liberation of the pebbles by coarse-grinding alone was suggested to be feasible.

7.6.1.2 Coverdale ($46^{\circ}03':64^{\circ}45'$)

The Killarney Oil and Gas Development Company Ltd. (Geren, 1971), based upon information provided in old (1919 and 1931) New Brunswick Gas and Oilfields Ltd. borehole logs, intersected titaniferous preCarboniferous basement rock units in diamond drillholes near Coverdale south of Moncton. Coincident airborne magnetic anomalies delineated an "area of interest" to Killarney.

Killarney identified two titaniferous gabbroic rock units lying beneath 100 to 125 metres of Carboniferous sediments. The most common unit is a fresh, coarsely crystalline, light-grey, anorthositic gabbro containing accessory ilmenite-magnetite oxides concentrated along fractures in feldspar crystals. The

second unit is an altered, soft, coarsely crystalline, dark green, amphibolitic rock with disseminated accessory ilmenite and magnetite. Drill core analyses indicate a TiO_2 content of 6.9% and an Fe content of 13.4%.

7.6.1.3 Others

Numerous occurrences of ilmenite have been reported throughout the province, hosted by diverse rock types. However, none of these occurrences appears to contain anomalous concentrations. Such occurrences, unearthed in the process of completing this report, are included herein, but this list is not intended to be a complete one. Our efforts concentrated on pinpointing those occurrences or geologic environments which might offer potential for development, not on listing titanium-bearing mineral occurrences.

Lutes (1979) identified pyrrhotite, pyrite and ilmenite as common accessories in calc-silicate rocks of the Hartin Formation, located west of Canterbury.

Ruitenberg (1976) listed ilmenite as an accessory mineral in fragmental pyrrhotite-chalcopryrite ore in the Heath Steele A and C zones. He also listed rutile in two of the three recognized mineral assemblages at Mount Pleasant.

7.6.2 Areas of Potential

7.6.2.1 Taylor Village

The Taylor Village anatase occurrence offers the best potential for successful titanium exploration. Its value lies as much in its usefulness as an exploration model as in

the development potential of the actual occurrence. The fact that the titanium mineralization is in the form of anatase (TiO_2) makes this occurrence and others, if identified, particularly attractive. Pigments, manufactured from titanium oxides, account for 90% of the titanium consumption in the United States. This demand for titanium oxide results in the manufacture of synthetic rutile (TiO_2) from ilmenite. The availability of natural titanium dioxide (in this case, anatase) would enhance the economics of any deposit which might be identified.

The prospects for similarly mineralized conglomerates in the Hopewell Group are considered to be excellent. In addition, similar rock types in other Moncton Sub-basin rock units are known and are likely hosts of similar mineralization (e.g. Horton Group conglomerates).

The exploration model becomes more tenable when the Coverdale titanium occurrence is taken into consideration. This occurrence, as described in Section 7.6.1.2, consists of a titaniferous (ilmenite) gabbro underlying the Westmorland Uplift. The occurrence therefore documents the existence of ilmenite-rich rocks within one of the source areas of sediments for Taylor Village-type titanium occurrences.

The potential of paleoplacers in Pennsylvanian sediments is unknown; however, these rocks are known to host abundant fluvial deposits derived from heavy mineral-bearing source rocks.

7.6.2.2 Others

The potential for offshore placers along the New Brunswick coastline is largely unknown. Hale and McLaren (1984) assembled the available data on the subject, with the result

that the Federal Department of Energy, Mines and Resources through the Atlantic Geoscience Centre has awarded a contract to Earth and Oceans Research Limited of Dartmouth, Nova Scotia to specifically examine this question. The results of that study, which is currently in preparation, will apparently indicate that a lack of useful sample points and analyses hampers the evaluation; additional sampling will be called for (J. Thibault, personal communication, 1988). Hale and MacLaren do indicate that "large" deposits of marine sand and gravel have a "fair to good" likelihood of availability offshore from Chatham and Saint John. These two areas were singled out specifically as urban centers requiring sources of aggregate and heavy mineral content was not considered; however, the question of availability of sufficient volumes of material is a factor in determining potential.

It should be kept in mind that evaluation of placers or paleoplacers should be approached with total heavy mineral content in mind, not just one mineral (e.g. rutile). Invariably the production of heavy minerals from placer deposits around the world yields two, three or more heavy minerals.

7.7 Processing

7.7.1 Mining and Concentrating

Titanium-bearing heavy mineral sand deposits are usually mined by dredging. The most common method is the suction type, although the bucket-ladder type is sometimes used. The dredge floats in its own lake, and uses the method of digging forward and stacking tailings aft. The processes of desliming, removal of organic matter, and rough concentration take place either on the dredge itself or on close-coupled barges towed behind the dredge. Where dredges are not practicable and draglines

are used, the concentration process is undertaken in a permanently situated plant.

Rough concentration - namely, the separation of heavy minerals from the lighter quartz-feldspar-mica fraction - is usually accomplished by wet-gravity methods. The standard method for this separation has been the Humphreys spiral. However, it begins to lose effectiveness at sizes finer than 150 to 200 mesh. The pinched-slucice concentrator will separate the finer sizes but it is sensitive to variations in pulp-flow. A flotation process can also be used for the separation of fine-sized materials. In Australia, the Reichert cone concentrator, which operates on the pinched-slucice principle, has been very successful for large tonnage operations.

The wet-mill concentrate is usually dried in a rotary kiln before further treatment. The process that follows will depend on the type of material to be treated. Ilmenite and rutile are usually removed together by electrostatic separation. Ilmenite is produced by subjecting the dried wet-mill concentrate to high-intensity magnetic separation, the rutile fraction is further cleaned by screening and additional electrostatic separation. Zircon and monazite products are recovered from the non-conductive fraction of the wet-mill concentrate by a combination of gravity, electrostatic, and high-intensity magnetic separation.

In Canada, Norway and Finland, ilmenite is mined from hard-rock deposits using, with the exception of Finland, open-pit mining. After crushing, grinding, and recovery of magnetite by wet-magnetic separation, an ilmenite concentrate containing 45% to 47% TiO_2 is produced by flotation at Tellnes, Norway. Tellnes also makes a by-product sulphide concentrate containing 4% to 4.5% nickel and 2% to 2.5% copper. At Allard Lake, Quebec, ore grading 32-36% TiO_2 is shipped from the mine

to the beneficiation plant, whereas the lower grades are shipped, as mined, to steel companies as a substitute for fluorspar, and to construction companies as a component of heavy aggregate.

The Allard Lake ores are processed using a unique method, whereby the ore is crushed and ground, concentrated by gravity methods, roasted to remove sulphur, mixed with a reducing agent, and smelted in an electric arc furnace. A commercial grade of low manganese pig iron is produced, called Sorelmetal. The resulting slag, called Sorelslag, contains an 80% TiO_2 concentrate. Since the iron content of the slag is low, it reduces the quantity of iron sulphate in the liquid effluents from pigment plants.

A technique similar to that used to process Allard Lake ore is also used by Richards Bay Minerals to produce titanium slag. The ilmenite from the dry mill is roasted and then passed over magnetic separators which discard an impure fraction to be stockpiled for retreatment, thus leaving a clean ilmenite. Anthracite, which is heated in a charring plant to reduce its volatile content to below 3%, is mixed with the clean ilmenite and both are fed to the smelter furnaces. The open arc furnaces reduce the ilmenite to metallic iron and slag, each of which is tapped off at regular intervals. The slag is tapped into slag-bedded rail cars and passed through spray cooling and then offloaded onto a stockpile for final air drying. A crushing and screening process completes the slag processing.

7.7.2 Synthetic Rutile

Synthetic rutile is made from ilmenite and contains 90-95% TiO_2 , nearly as high as that of natural rutile (94-96% TiO_2). Rutile substitutes are known as synthetic, artificial or reconstituted rutile, and as beneficiated or upgraded ilmenite.

Around 85% of titanium mineral production is used in the manufacture of titanium dioxide pigments. Most ilmenite is used in the manufacture of titanium dioxide pigments by the sulphate process, whereas rutile is used for the manufacture of titanium dioxide pigments by the chloride process and also in the manufacture of titanium sponge. Owing to the environmental problems associated with the sulphate process, many developed countries, especially the U.S.A., have concentrated on building chloride plants, thereby increasing the demand for rutile.

The main consideration in developing synthetic rutile processes is the removal of iron and other impurities from ilmenite. It is also desirable to have a low magnesium and calcium content. The major processes that have been developed fall into three groups:

- 1) Those in which the iron content of the ilmenite is essentially reduced to the metallic state and subsequently removed from the titania by chemical extraction or by physical separation.
- 2) Those in which the undesirable iron and other metal oxides are removed by leaching with mineral acid. Depending on the particular ilmenite used, a pre-treatment such as partial oxidation and/or partial reduction of the iron content may be required to attain Fe^{+2} prior to leaching.
- 3) Those in which some or all of the metal content in the ilmenite is converted by chlorination to their respective volatile chlorides. These are then separated into individual compounds or groups of compounds for subsequent processing.

In 1977, Laporte Industries Ltd. had developed a process for the beneficiation of ilmenite, which involves a new variation of the oxidation-reduction pretreatment of ilmenite

for acid leaching, using a high temperature (900°C to 950°C) for the oxidation treatment and controlling the reduction step so that the proportion of iron in the ferrous state is about 86 to 92%. The treated ore requires only a single-stage leach for the satisfactory removal of iron and other impurities. After washing and calcination, the beneficiated ilmenite typically contains 95.5% TiO_2 and has the same particle size as the original ore.

7.7.3 Titanium Dioxide

Titanium dioxide is produced commercially by two methods, requiring different raw materials. In the sulfate process, ilmenite or titanium slag is reacted with sulfuric acid, a portion of the contained iron sulfate is crystallized and removed, and the titanium hydroxide is precipitated, filtered, and calcined.

In the chloride process, rutile is converted to titanium tetrachloride by chlorination at 850° to 950°C in the presence of petroleum coke. All commercial plants in the United States use fluid-bed chlorinators, although static-bed systems may be used. Rutile is the preferred raw material for making titanium tetrachloride, although ilmenite and titanium slag can be used.

Titanium tetrachloride so prepared may be used both in making pigment and in reducing to metal; there is little difference in the specifications. In making pigment, the titanium tetrachloride is oxidized with air or oxygen, and the resulting fine-size titanium dioxide is calcined at 500° to 600°C to remove residual chlorine and any hydrochloric acid that may have formed in the reaction. Aluminum chloride is added to the titanium tetrachloride to assure that virtually all of the titanium is oxidized in the rutile crystalline form.

7.7.4 Titanium Sponge

The commercial production of titanium sponge is a relatively recent development, dating back to the early 1950's. The first commercial method to be developed was the Kroll process which involves the reduction of titanium tetrachloride in an inert atmosphere using magnesium metal. The only other process in commercial use at present is the Hunter process, developed by ICI, U.K. The process uses sodium to reduce the raw material into titanium sponge. An electrolytic reduction process has been developed, but commercial production has not yet begun.

In Japan, a variation of the Hunter process, developed by New Metals Industry, reduces the two step process into a one step reaction. This variation is expected to lead to the development of a continuous system as an alternative to the present batch system.

The fact that most producers use the Kroll process does not mean that this process is superior to the Hunter process, but rather that magnesium is easier to handle than sodium.

A major disadvantage of both the Kroll and Hunter reduction processes is that they can only operate as batch processes. This limits production capacity. Therefore, companies have been looking towards new production processes, capable of continuous production. One possibility is the production of electrolytic sponge.

7.7.5 Titanium Metal

Since titanium sponge is porous, it has to be melted to obtain titanium metal. Nearly all commercial metal has been produced by the double arc melting process employing consumable

electrodes in an inert atmosphere or a vacuum. The power required to produce 1 pound of titanium metal ingot is about 2 to 2.5 kilowatt hours.

A non-consumable electrode vacuum melting process is now being used more widely.

The manufacturing process from ingot to the final products is usually carried out by hot forging, to give conveniently sized intermediate blooms or slabs before the subsequent conversion to the stock sizes and shapes of standard mill products. These include sheet, strip, plate, bar, billet, wire, foil, and tubing. Titanium when hot has a strong affinity for absorbing many deleterious elements, but despite this it is very easy to hot forge the ingot. Ingot breakdown is invariably carried out by press forging, as violent deformation by other means may cause internal cracking of the as-cast structure. Electric pre-heating furnaces for this are usually preferred because they afford better atmosphere and process control. In commercial practice, heat and forging cycles must be kept as short as possible, and a dry, slightly oxidizing furnace atmosphere is advisable. Speed is vital, and forming time at elevated temperatures must not be delayed. The contaminated surface layer will then be as thin as possible and can usually be removed by a descaling or pickling process.

Titanium metal powder is usually produced by reacting the metal with hydrogen, crushing the resulting brittle titanium hydride, and then heating the hydride in a vacuum to remove the hydrogen.

8.0 Zirconium

8.1 Properties

Zirconium metal has an atomic number of 40 and an atomic weight of 91.22. The metal's melting point is 1830°C and has a specific gravity of 6.5. Because of its low thermal neutron absorption cross section, low radioactivity after radiation exposure and transparency to thermal neutrons, hafnium-free zirconium is used as a structural material for nuclear reactors. The metal has excellent corrosion resistance which is imparted to alloys in which it is a component. In magnesium alloys it increases strength and ductility. These properties aside, the bulk of the zirconium consumed is in the form of the mineral zircon and zirconium oxide.

8.2 Saleable Forms and Price

The main forms in which zirconium is used commercially are in its mineral form (principally zircon), as an oxide, compound or pure metal. Trade in zirconium is conducted in three basic forms, mineral concentrates, compounds and metal. Hafnium, because it is extracted from zirconium to be used in the nuclear industry, is an integral part of zirconium metal production and marketing.

Prices for these various forms of zirconium plus hafnium were published by the U.S. Bureau of Mines to cover 1985.

concentrates:

zircon	
U.S., standard grade, f.o.b.	
Starke Fl., bulk	\$US175/ton
U.S., 75% min. zircon and Al silicates,	
f.o.b. Starke, Fl., bulk	\$US99/ton
non-U.S. sand, 65% ZrO_2 , f.o.b.,	
bulk	\$US86-92/tonne
U.S., granular, bags, bulk rail	\$US165-177/ton
U.S., milled, 200-+235 mesh,	
rail in bags	\$US225/ton
baddeleyite, non-U.S. conc.	
96%-98% ZrO_2 , minus 100-mesh	\$US0.50/lb.
99+% ZrO_2 , minus 325-mesh	\$US0.97/lb.

Compounds:

zirconium oxide	
powder, commercial grade, drums,	
1 ton min.	\$US4.25/lb.
electronic grade, drums, 1 ton min.	\$US7.25/lb.
insulating, stabilized, 325°F,	
drum, 1 ton min.	\$US3.31-3.82/lb.
insulating, unstablized, 325°F,	
drums, 1 ton min.	\$US3.55-3.75/lb.
dense, stabilized, 30°F, drums,	
1 ton min.	\$US2.82/lb.
zirconium oxychloride	
crystal, cartons, 5 ton lots	\$US0.91-1.04/lb.
zirconium acetate solution	
25% ZrO_2 , drums, carlots, 15 ton min.	\$US0.97/lb.
22% ZrO_2 , drums, carlots, 15 ton min.	\$US0.78/lb.
zirconium hydride	
electronic grade, powder, drums,	
100 lb. lots	\$US31.75/lb.

Metal:

powder	\$US75-150/lb.
sponge	\$US12-17/lb.
sheets, strip, bars	\$US20-40/lb.

Hafnium, sponge	\$US80-130/lb.
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8.3 Production Statistics

	zirconium concentrates					
	1981	1982	1983	1984	1985 ^e	1986 ^e
	(tonnes)					
Australia	435,592	463,911	383,491	455,944	441,350	470,000
Brazil	6,019	5,011	13,833	6,395	7,007	-
China ^e	15,015	15,015	15,015	15,015	15,015	-
India	12,439	10,516	11,431	11,830	13,650	-
Malaysia	1,311	2,154	2,556	7,638	9,009	-
South Africa	100,100	127,400	162,784	153,598	200,655	150,000
Sri Lanka	3,276	5,807	5,738	3,719	3,713	-
Thailand	105	197	199	291	300	-
U.S.S.R. ^e	72,800	81,900	81,900	81,900	86,450	85,000
U.S.A.	w	w	w	w	w	85,000
Other	-	-	-	-	-	40,000
Total	646,657	711,910	676,948	736,329	777,149	830,000

e - estimated

w - withheld

8.4 Uses

8.4.1 Applications

Approximately 95% of all zirconium consumed is in the form of the mineral, zircon, and in the oxide and other compounds. The remainder is consumed as zirconium-containing alloys and in zirconium metal and alloys used as structural materials for nuclear reactors and chemical processing equipment.

The mineral zircon is used chiefly for facings on foundry molds, which, on the basis of zirconium content, account for more than half of the use of the element. Milled or ground zircon also is used in refractory paints for coating the outside of molds. Zircon facings increase resistance to metal penetration and afford a uniform finish to castings. Zircon, in the form of refractory bricks and blocks, is widely used in glass furnaces

and in hearths for containing molten metals. Zircon is also used in manufacturing fused cast and bonded alumina-zirconia-silica base refractories for glass tank furnace use and in alumina-zirconia snagging wheels. Zirconium oxide refractories have high light reflectivity and good thermal stability. Zircon also is used as refractory material for dies used for extruding various materials. The oxide is used chiefly as an opacifier and pigment in enamels and glazes for pottery and other ceramic products.

Republic of South Africa baddeleyite ore is used principally in the manufacture of alumina-zirconia abrasives and also in ceramic colors, refractories, and for other uses.

There are many small but important applications for zirconium compounds in miscellaneous chemical products. Tooth pastes and powders containing stannous hexafluorozirconate are reportedly effective in preventing tooth decay. A water slurry of zirconium oxide can be used in polishing optical glass. Zirconium compounds are used in polymeric waxes; zirconium sulfate is used in leather tanning agents. Zirconium alkoxides are added to paint to inhibit rust, are used as a flexible film coating in stainless steel, and are added to ink to promote drying and prevent smearing. The alkoxide and acetate forms are used as water repellents for leather and textiles.

Because of its low thermal neutron absorption cross section, low radioactivity after radiation exposure, and transparency to thermal neutrons, hafnium-free zirconium is used as a structural material for nuclear reactors employing pressurized-water heat exchangers. Both high-purity and zirconium-base alloys (Zircalloys) are used. Relatively small quantities of shredded reactor-grade foil are used in camera flashbulbs to provide a quick ignition and greater and longer light intensity.

A small quantity of commercial-grade zirconium metal and alloys (principally Mo, Ti, Zr alloys and Zircalloys) is used in the chemical industry as components in heat exchangers, acid concentrators, tank shafts, valves, pump housings, fan wheels, high-speed agitators, electrode assemblies, steam jet exhausts, tubing, pipes and pipe fittings, spinnerets, and crucibles.

An addition of less than 1% zirconium increases the strength and ductility of magnesium metal and of magnesium-zinc, magnesium-rare-earth, and magnesium-thorium alloys. Additions of up to 1% zirconium to columbium-base alloys are vital to assure corrosion resistance to alkali liquid metal at elevated temperatures and to contribute strength to the alloys. Zirconium-columbium alloys are used in superconducting magnets.

8.4.2 Alternatives

Stainless steel, titanium and tantalum are substitutes for zirconium in nuclear and many corrosion-resistant applications.

8.5 World Deposits

8.5.1 Zirconium Geochemistry and Mineralogy

In the order of 40 species of zirconium minerals have been reported. Over half are silicates, the bulk of the remainder are oxides with few carbonates and sulphates. Zirconium is produced from two minerals, baddeleyite, ZrO_2 , and zircon, ZrSiO_4 .

Zirconium is one of the more abundant trace elements in igneous and sedimentary rocks. Zirconium oxides are usually

found in nepheline syenites and in carbonatites of alkali-rich ultramafic massifs. Zircon, the commonest silicate, is found in nearly all rock types. The other zirconium silicates are present mainly in alkali-rich and agpaitic (Section 12.0) rocks and are not normally found in rocks which contain zircon.

The similar chemical and physical properties of zirconium and hafnium result in their close association and difficulty in their separation. All zirconium minerals contain hafnium, usually in concentrations up to 2%.

8.5.2 Deposit Classification

Zircon is mainly recovered from beach placer deposits where it is associated with other heavy minerals such as ilmenite, rutile and monazite. Baddeleyite in association with zircon is mined from placer deposits which originate from veins consisting essentially of baddeleyite and zircon.

Zircons may be of igneous, metamorphic and, to some extent, authigenic (Section 12.0) origin and are resistant enough to sometimes survive several cycles of erosion. Zircons can thus accumulate in high energy environments and may become concentrated in clastic sediments, especially sands. This process of natural concentration through weathering and erosion, particularly of granitic rocks, has led to deposition of mineable concentrations of heavy mineral sands containing zircon.

8.5.2.1 Australia

Australia is the dominant supplier of zircon concentrates, although its proportion of production has declined recently compared to South Africa. All of Australia's production

is derived from heavy mineral sands operations. Approximately 75% of Australia's output comes from Western Australia with the balance from the east coast. Allied Eneabba Ltd. is the largest Western Australian mineral sand producer. Renison Goldfields Consolidated Ltd. is reported to have purchased, in 1985, the 50% interest in this company formerly held by E.I. du Pont de Nemours. TiO_2 Corporation NL produces zircon from its Cooljarloo and Jurien deposits in Western Australia. On the east coast, Consolidated Rutile Ltd. is in production on North Stadbrook Island.

8.5.2.2 South Africa

In South Africa, zircon concentrate from heavy mineral sands is produced by Richards Bay Minerals, co-owned by Union Corp. Ltd. (S. African) and QIT-Fer et Titane (Canadian), at Richards Bay north of Durban. Baddeleyite concentrates are produced at Phalaborwa by Phosphates Development Corp. (FOSKOR) and by Palabora Mining Co. Ltd. (PMC) from contiguous deposits in the Palabora igneous complex. These baddeleyite concentrates are co-products from copper, phosphate and iron operations.

8.5.2.3 U.S.A.

E.I. du Pont de Nemours and Co. and Associated Minerals Consolidated (USA) Ltd. (a subsidiary of Associated Minerals Consolidated Ltd. of Australia) recover zircon concentrates as a by-product from their heavy mineral sands operations in Clay County, Florida. These were the only recorded U.S. producers of zircon in 1984.

P.W. Gillibrand Co. began production of heavy mineral sands at Soledad, California in 1985. These sands contain 33% ilmenite, 20% magnetite, 27% apatite and 4.5% zircon.

8.5.2.4 Others

The balance of the world's production of zirconium ore from individual countries outside the U.S.S.R. is very much smaller than the outputs from Australia and South Africa. No details of the U.S.S.R.'s production are readily available. Except for Brazil, the balance of the world's production also comes from the processing of heavy mineral sands. Brazilian zirconium production is apparently derived both from heavy mineral sands and the mining of baddeleyite at Poco de Caldas in Minas Gerais State by Minegral-Cia. Brasileira de Mineracao Industria e Comercio S.A.

8.6 New Brunswick Potential

8.6.1 Occurrences

Zircon is a common and widely distributed accessory mineral in all types of igneous rocks. It is especially frequent in the more silicic plutonic rocks such as granite, granodiorite, syenite and monzonite and is relatively abundant in nepheline syenite. Zircon is also found in crystalline limestone, gneiss and schist. These associations are common and well documented in New Brunswick. However, as zircon is usually present only as an accessory mineral disseminated through the host rock, its concentration is too low for economic extraction. Reported occurrences of anomalous concentrations of zircon in either modern or paleo-placers in the province are almost nonexistent.

8.6.1.1 Hayesville and Napadogan Map-Areas

In 1959 and 1960 Poole and Lachance completed analyses of placer pan concentrates collected during bedrock mapping

of the Hayesville (NTS 21J/10) and Napadogan (NTS 21J/7) map-areas. Zirconium and yttrium distribution parallel one another, and most "higher-than-normal" values appear in concentrates draining granitic rocks of all ages, apparently reflecting the accessory mineral assemblages. A single concentrate containing anomalous zirconium and yttrium originated from an area underlain by Silurian greywacke in the centre of the Napadogan map-sheet; no explanation for this anomaly is available.

8.6.2 Areas of Potential

The potential for identification of exploitable zircon bearing placers in New Brunswick is limited by two constraints: the lack of data detailing zirconium content of the surficial deposits in the province and the relatively small volumes of those deposits. The latter constraint simply reduces the statistical probability of successful exploration. The potential of paleo-placers is unknown, although Carboniferous sedimentary rock units are known to include abundant fluvial deposits derived from zircon-bearing source rocks.

The potential for offshore placers along the New Brunswick coastline is largely unknown. Hale and McLaren (1984) assembled the available data on the subject, with the result that the Federal Department of Energy, Mines and Resources through the Atlantic Geoscience Centre has awarded a contract to Earth and Oceans Research limited of Dartmouth, Nova Scotia to specifically examine this question. The results of that study, which is currently in preparation, will apparently indicate that a lack of useful sample points and analyses hampers the evaluation; additional sampling will be called for (J. Thibault, personal communication, 1988). Hale and MacLaren do indicate that "large" deposits of marine sand and gravel have a "fair to good" likelihood of availability offshore from Chatham and

Saint John. These two areas were singled out specifically as urban centers requiring sources of aggregate, and heavy mineral content was not considered; however, the question of availability of sufficient volumes of material is a factor in determining potential.

It should be kept in mind that evaluation of placers or paleoplacers should be approached with total heavy mineral content in mind, not just one mineral (e.g. zircon). Invariably the production of heavy minerals from placer deposits around the world yields two, three or more heavy minerals.

8.7 Processing

8.7.1 Mining and Concentrating

Sand deposits are usually mined with floating suction or bucket-line dredges which handle up to 1,200 tons of material per hour. The sand is treated by wet-gravity methods, using spirals, cones, sluices, or jigs to produce a bulk, mixed, heavy mineral concentrate containing zircon, the titanium minerals rutile and ilmenite, and other marketable minerals such as monazite (a mineral containing rare earth elements).

The Reichert cone concentrator, a combination of cones and pinched sluice trays developed for use in the lower-grade Australian heavy sand operations, is used widely in their East and West Coast plants as high capacity rougher devices treating feeds between 2 mm and 350 mesh.

The specific gravity of zircon (4.7) enables it to be concentrated with other heavy minerals by gravity methods. Clean zircon is produced from heavy-mineral concentrates by a combination of drying, screening, electrostatic, and electro-mag-

netic processes. Zircon, in contrast to ilmenite, rutile, and many other heavy minerals, is nonconductive and can be separated, with monazite, by electrostatic methods. Monazite, which is slightly magnetic, can be separated from zircon by electromagnets. To obtain clean zircon, the zircon-rich tailings from the electrostatic-electromagnetic processes are again subjected to gravity concentration (spirals or tables) to eliminate light, nonconductive minerals such as quartz and kyanite. The enriched product is usually dried at 1,200°F to remove organic stainings, then treated in high tension separators and induced roll magnetic separators to remove residual conductive and magnetic minerals. A 99% zircon product is usually obtained by these methods.

8.7.2 Nonmetal Production

Zircon intended for use in foundries is graded and sized and, in many cases, wet- or dry-ground prior to marketing. Zirconium oxide for refractory, ceramic, and glass applications is produced directly from zircon by either electric arc or plasma fusion techniques, or by reaction with alkaline earth and alkaline salts (e.g., dolomite, soda ash) in the solid state, at a high temperature followed by leaching to remove impurities.

Other compounds of zirconium such as the hydrous or carbonated oxide, the acetate, sulfate, fluoride, chloride, and organic complexes and various zirconates are usually prepared from zirconia or its salts by reacting with other chemicals.

The plasma method for producing zirconia employs heating a finely divided zircon concentrate above its dissociation temperature, avoiding particle coalescence, to form extremely small zirconia crystallites and glassy amorphous silica. The hot dissociated zircon is quenched rapidly and glassy silica leached out with a sodium hydroxide solution leaving the insoluble

zirconia crystallites. The production of either zirconia or a zirconium salt involves heating a stoichiometric balanced mixture of limestone and zircon at a selected time and temperature to form calcium zirconate and tricalcium silicate clinker. The clinker is carefully cooled to first convert the tricalcium silicate to dicalcium silicate and lime. Further cooling results in the disintegration of the clinker into a very fine powder composed of dicalcium silicate and lime and coarser calcium zirconate crystals which are readily classified. The acid soluble calcium zirconate crystals are treated with either acids or other reagents forming oxides or salts.

8.7.3 Metal Production

Commercial-grade zirconium is produced by blending zircon with coke which is then reacted or fused in an electric arc furnace. The carbon and nitrogen from air react with zirconium to yield zirconium carbonitride containing about 85% zirconium. The carbonitride is chlorinated to crude zirconium tetrachloride which is reduced to zirconium metal with magnesium metal under an inert atmosphere. The reduction stage is called the Kroll process. The resulting mixture of zirconium metal and magnesium chloride is vacuum-distilled to remove the magnesium chloride. The residual zirconium sponge contains about 2% hafnium but is still suitable for most non-nuclear applications. Current industry practice uses a zirconium tetrachloride produced by chlorinating zircon directly instead of the carbonitride.

The separation of hafnium from zirconium is costly but necessary in order to produce the hafnium-free zirconium required for nuclear reactors. Separation processes that have been suggested include solvent extraction, ion exchange, distillation, selective partial reduction, vapor phase dechlorination, fractional precipitation, and caustic leaching.

Of these, the solvent extraction method has been adopted to the greatest extent. In this process, crude or commercial-grade mixed tetrachloride is dissolved in hydrochloric acid containing ammonium thiocyanate and fed to the top of a vertical glass column. A solvent (methyl isobutyl ketone) enters at the bottom of the column. Hafnium thiocyanate dissolves preferentially in the solvent as it passes upward through the column. The hafnium thiocyanate is stripped from the organic phase with sulfuric acid, at which time it is converted to the sulfate. Hafnium is precipitated as the hydroxide and is then calcined to about 99% hafnium oxide.

The resulting zirconium sponge is crushed, compacted into consumable electrodes, and vacuum-melted in an inert atmosphere into ingot. The ingot is used as consumable electrode to produce second-melt ingot, which is machined and readied for fabrication.

The deBoer-van Arkel process, first described in 1925, is essentially a refining process and was commercially adopted in 1945. Commercial or hafnium-free zirconium metal is reacted with iodine vapor at 200°C to form zirconium tetraiodide. The gaseous halide is transferred to a connecting vessel, leaving most impurities except hafnium in a solid state in the reaction chamber. At $1,300^{\circ}\text{C}$ the reaction is reversed, depositing very high-purity elemental zirconium on a heated filament and regenerating iodine vapor for recycling.

9.0 Conclusions and Recommendations

At the present time, no deposits of specialty metals are known to exist in the province. There have, however, been recognized a number of occurrences which point towards the presence of rock units which could host such deposits. Investigations are required in order to determine the potential of these occurrences and of the rock units identified. This study and the implementation of its recommendations are aimed at determining the probability of successfully identifying such a deposit or deposits.

9.1 Beryllium

9.1.1 Vicinity of the Burnthill and Dungarvon Stocks

The area in the vicinity of the Dungarvon (including the Rocky Brook and Trout Brook lobes), Sisters Brook, Buttermilk Brook and Burnthill plutons in west-central New Brunswick warrants exploration attention. Although the occasional presence of large crystals of beryl should not be overlooked, a larger volume, lower grade surface deposit of beryllium offers more potential for commercialization. The "Roadside" ore zone at Spor Mountain, Utah yields ore ranging from 0.4 to 1.0% BeO (0.14-0.36% Be), whereas the Trout Brook lobe has yielded samples, collected for their tin-tungsten rather than their beryllium content containing beryllium approaching these concentrations. The identification of nonpegmatitic beryllium mineralization should be the thrust of any beryllium exploration in the Burnthill-Dungarvon area.

The area has been examined in some detail for the purposes of bedrock mapping and tin-tungsten exploration. Government, both provincial and federal, and private sector geologists

have acquired a considerable quantity of data for the area, some of which is in preparation for publication (Fyffe, 1988, personal communication). This data must be assembled and synthesized, not an onerous task given the detailed bedrock mapping available for the area.

The lack of geochemical data on beryllium is the single largest obstacle to determining the area's potential. Sufficient sampling and analyses are required to determine the beryllium distribution in the various rock types, and particularly in the greisens known to exist in the area. In conjunction with the sampling required to fulfill this task a detailed determination of the extent of the greisens and mineralized pegmatites should be undertaken. The available data suggests that the eastern margins of the Rocky Brook and Trout Lake lobes of the Dungarvon pluton warrant particular attention. The number of beryl, fluorite and greisen occurrences in the Rocky Brook and Trout Brook granites could, however, be a function of the degree to which they have been studied.

9.1.2 Juniper Barrens Granite

The extent of the bimicaceous granite and pegmatite veins in the eastern contact zone of the Juniper Barrens Granite warrants investigation. Similarly, the beryllium content of these veins, except for the noted occurrences of beryl at certain locations, is unknown and should be determined.

9.1.3 Others

The Zealand Station beryllium occurrence is currently under mineral claim and is being evaluated.

The various occurrences listed in section 3.6.2.3 warrant at least cursory investigation. Acquisition of considerable geochemical data on beryllium and integration of this with the known geology of the occurrences is required. Site visits for the purpose of sample collection must be preceded by synthesis of the available site data to assure efficient sampling procedure; the geological data base may also be augmented where necessary during the site visits.

9.2 Gallium

The association of gallium with epigenetic, low-temperature carbonate-hosted sphalerite deposits suggests that exploration for such deposits in New Brunswick should include evaluation of gallium content. The focus of any such exploration would likely be the Windsor Group of the Moncton subbasin. The expected concentration of gallium in such sphalerites requires that the deposit be of sufficient size to allow economically viable zinc production, with gallium recovered as a by-product; the reverse scenario is very unlikely.

The enrichment of gallium in gossanous materials suggests that gossans associated with the Bathurst-camp base metal deposits warrant investigation. The gallium content of "fresh" ore, and the extent of surficial weathering, will determine the gallium content of the gossans. If present in sufficient grade and tonnage, the presence of gallium could enhance the viability of a deposit under investigation.

In view of the ongoing combustion of indigenous coal in the province, a knowledge of the gallium content of both the raw coal and resultant ash should be made available. Similarly, the current experimental work being undertaken in oil shale utilization and particularly in coal-oil shale-limestone co-com-

bustion suggests that the gallium content of these raw feeds and resultant ashes should also be determined.

It is advisable that analyses for gallium be accompanied by analyses for germanium.

9.3 Germanium

As gallium and germanium show a close geochemical association, the recommendations made for the assessment of the gallium content of various rock units and/or specific mineral occurrences, also apply to germanium. All sampling and analyses undertaken for germanium should include gallium.

9.4 Rare Earth Elements and Yttrium

Except for exploration for monazite deposits in the early years of the rare earth (and thorium) industry, most rare earth deposits have been discovered during the search for other minerals. Because many rare earth and yttrium minerals are naturally radioactive or associated with radioactive minerals, many discoveries have been made during uranium exploration; however, few are economic. The rich bastnaesite deposit at Mountain Pass was discovered by a prospector attracted to the area by the radioactivity of minerals associated with the bastnaesite. Most monazite deposits were discovered as a result of prospecting for gold, titanium, tin, and zirconium in alluvial and beach sand deposits.

Those areas of New Brunswick indicated as having potential for hosting REE mineralization were delineated as a result of evaluations conducted for other elements. Since the primary focus in each case was other commodities, little

information concerning the occurrence of the REE's is available. It is therefore necessary to assess the implications of each occurrence and through the acquisition of additional data determine the significance of that occurrence. The result of such a task may very well be the discounting of these occurrences in themselves, although the data acquired may point towards other locations and/or rock units more favourable to hosting REE. The absence of carbonatites in the province renders the possibility of discovering a carbonatite-related REE deposit impossible. Similarly, the possibility of identifying a placer-type REE deposit is remote. However, the occurrences do indicate the presence of REE's in rock units similar to those hosting other genetic types of REE deposits currently in production elsewhere in the world.

9.4.1 Mt. Pleasant

REE minerals are known to exist in the Mt. Pleasant deposit; however, their mode of occurrence, grade and metallurgy are largely unknown. Initially it should be determined whether these types of studies have been carried out on the ore, gangue or country rock at Mt. Pleasant. If they have not, it is possible that the geological, mineralogical and geochemical data required to evaluate the REE potential of the deposit are available in the form of drill logs and drill core. Resolution of these questions may only require acquisition, integration and assessment of such data. This task should begin with a discussion with those intimately familiar with the geology and mineralogy of the deposit.

9.4.2 Geochemical Occurrences

The occurrences at Lutes Mountain, in the Hayesville

and Napadogan areas, at Lake Utopia, and at Manners Sutton must be authenticated through duplication of geochemical analyses. Assuming the anomalous values can be duplicated, the details of the mineralogy and geology of the occurrences must be investigated. This information is required to trace the extent of the mineralization and determine whether the occurrences possess any potential in terms of total grade or size; it may also point to related rock units which could offer potential.

9.4.3 Apatite and/or Gabbro Related Occurrences

The Sheba occurrence appears to be of minor interest; however, if the drill core cut on the property is available, the occurrence warrants examination. Initially, duplication of the analytical results and determination of the mineralogy and geology of the occurrence is required.

The model offered by the Benjamin River gabbro-related apatite occurrence implies that potential also exists in other gabbroic intrusions, as listed in section 6.6.2.4. These include the Owl Lake area of the Becaguimec Lake gabbro, and possibly other portions of that pluton. In addition, the gabbros mapped at Dalhousie, Eel River, Blue Mountain, Jacquet River, Antinouri Lake, Gulquac Lake, Beadle Lake, Northeast Clearwater Brook, North Dungarvon River, Otter Slide Mountain, the Burnthill intrusion, Juniper and at Ayers Lake should be investigated. Several other slightly older gabbros mapped in the Chaleur Bay Synclinorium warrant similar consideration. Initially, determination of the detailed chemistry and mineralogy of the apatite at Benjamin River and the nature of the relationship between the apatite and magnetite is required. Marleau (1969) apparently had success in locating concentrations of apatite at Benjamin River by using aeromagnetism and soil geochemistry. If in fact the apatite and magnetite are closely associated,

then these techniques may be used to identify similar occurrences in the other gabbros listed above. Aeromagnetism could be used to identify those portions of an intrusion characterized by higher than normal concentrations of magnetite; ground magnetism and geochemistry would be employed in order to isolate specific targets.

9.5 Titanium

9.5.1 Paleoplacers

The Taylor Village anatase occurrence requires authentication in terms of the reported analytical results, mineralogy and mode of occurrence. If the occurrence does represent a titanium dioxide paleoplacer then its grade and magnitude warrants investigation. Of possibly greater significance is the model for further exploration that this occurrence provides. It is associated with Hopewell Group alluvial-fluvial conglomerates whose source rocks were either the Westmorland or Caledonia Uplifts. Both Uplifts host rocks known to contain titanium minerals - the Coverdale titanium occurrence, for example, is within the now buried Westmorland Uplift. Other alluvial-fluvial channel deposits within the Hopewell Group and also in the Horton Group, are all derived from either of the two Uplifts. Therefore, geological investigations followed by sampling and analysis are necessary to identify similar titaniferous occurrences. Upon identification, as is recommended for the Taylor Village occurrence, grade and magnitude must be determined.

The potential for paleoplacers in the Pennsylvanian sediments which occupy approximately one-third of the province is undetermined. These strata are known to host abundant fluvial deposits derived from heavy mineral-bearing source rocks. An orderly geological and geochemical assessment of these sedimentary

rocks is worthwhile. Such an assessment should address the full spectrum of heavy mineral assemblages.

9.5.2 Placers

The current investigations being undertaken through the Atlantic Geoscience Centre should continue to be monitored. As the projects proceed, New Brunswick must ensure that data necessary for the delineation of and promotion of its near-shore-offshore unconsolidated mineral deposits be acquired. If such potential off-shore deposits exist, titanium is likely to be present in relative abundance.

9.6 Zirconium

The potential of paleoplacers within Carboniferous (Mississippian and Pennsylvanian) sedimentary rocks is undetermined. Evaluation of Carboniferous alluvial-fluvial channel deposits for their titanium content should include analyses for zirconium. In fact, as recommended in Section 9.5.1 (Titanium-paleoplacers) any such assessments should address the full spectrum of heavy mineral assemblages.

The current investigations being undertaken through the Atlantic Geoscience Centre should continue to be monitored. As the projects proceed, New Brunswick must ensure that data necessary for the delineation of and promotion of its near-shore-offshore unconsolidated mineral deposits be acquired. Zirconium is among the elements likely to be contained within these potential mineral deposits.

9.7 Summary: Priorities

Analysis of the data assembled for the preparation of this report suggests that priorities can be assigned to the various recommendations which have been made. Assigned priorities imply a perceived possibility of successfully identifying an economically viable deposit; however, no assurance of this eventuality can be given. These priorities are based on the existing data, which, as has been pointed out in several instances, is lacking. However, priorities are required if work is to proceed, particularly given the number of recommendations made dealing with several commodities at several locations.

Authentication and assessment of the Taylor Village titanium occurrence (Section 9.5.1) should receive first priority. Based upon the assessment of the occurrence, efforts should then be made to identify additional similar occurrences, as recommended.

The recommendations for beryllium exploration in the vicinity of the Burnthill and Dungarvon stocks (Section 9.1.1), followed by those for the Juniper Barrens Granite (Section 9.1.2) may be implemented as second place priorities.

The Benjamin River REE-bearing apatite occurrence (Section 9.4.3) and the identification of additional similar occurrences should receive third priority.

The recommendations for the evaluation of the gallium-germanium content of various base metal deposit-related gossans, could proceed as priority four.

A heavy mineral (including among others, monazite, ilmenite and zirconium)/paleoplacer study of the Pennsylvanian sedimentary rocks of N.B. warrants completion as a fifth priority.

The initial investigations upon which to base such a study have been completed by the Department of Natural Resources.

The establishment of a modest program to establish the authenticity, and to study the geological and mineralogical characteristics of several apparently minor specialty mineral occurrences is warranted. The beryllium occurrences referred to in Section 9.1.3 and the REE occurrences referred to in Sections 9.4.1 and 9.4.2 are included in this category.

The lower perceived potential for gallium-germanium mineralization dictates that recommendations concerning them be assigned a lower priority. These recommendations include those related to

1. gallium analyses of Windsor Group-hosted sphalerite deposits.
2. gallium-germanium analyses of coal, oil shale and coal-oil shale ash.

The recommendations associated with nearshore-offshore unconsolidated mineral deposits need not be assigned a priority. Apparently a structure is in place and dialogue is ongoing aimed at meeting New Brunswick's requirements for evaluation of the potential of this resource.

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12.0 Glossary

- agpaitic - Said of a crystallization in the presence of an excess of alkali (esp. sodium), so that the amount of aluminum oxide is insufficient for the formation of aluminum silicates.
- alkaline - Said of an igneous-rock series that contains more sodium and/or potassium than is required to form feldspar with the available silica.
- allotriomorphic - Characterized by crystals not bounded by their own rational faces but with their forms impressed upon them by adjacent mineral grains.
- alluvial - Said of a placer formed by the action of running water, as in a stream channel or alluvial fan.
- aplite - A light-coloured intrusive igneous rock characterized by a fine-grained allotriomorphic (Section 12.0) - granular texture. May range in composition from granitic to gabbroic, but with no modifier is generally understood to mean granitic aplite.
- authigenic - Said of rock constituents and minerals that have not been transported or that crystallized locally at the spot where they are now found, and of minerals that come into existence at the same time as, or subsequent to, the formation of the rock of which they constitute a part.
- breccia - A coarse-grained rock, composed of angular broken rock fragments held together by a mineral cement or in a fine-grained matrix.
- carbonatite - A carbonate rock of apparent magmatic origin, generally associated with alkaline rocks.
- cataclastic - A rock containing angular fragments that have been produced by the crushing and fracturing of pre-existing rocks as a result of mechanical forces in the crust.
- cryptocrystalline - Said of the texture of a rock consisting of crystals that are too small to be recognized and separately distinguished even under the ordinary microscope.
- eluvial - Said of an incoherent ore deposit, such as a placer, resulting from the decomposition or disintegration of rock in place.
- epigenetic - Said of a mineral deposit of origin later than that of the enclosing rocks.

fluviatile - Of or pertaining to a river.

gangue - The valueless rock or mineral aggregates in an ore.

gossan - An iron-bearing weathered product overlying a sulphide deposit.

granophyre - An irregular microscopic intergrowths of quartz and alkali feldspar.

greisen - A pneumatolytically altered granitic rock composed largely of quartz, mica and topaz.

hiatal - Said of the texture of an igneous rock in which the sizes of the crystals are not in a continuous series but are broken; there are grains of two or more markedly different sizes.

hydrothermal - Of or pertaining to hot water, to the action of hot water, or to the products of this action, such as a mineral deposit precipitated from a hot aqueous solution, with or without demonstrable association with igneous processes.

lacustrine - Of or pertaining to a lake.

leptite - A granular quartzofeldspathic metamorphic rock formed by regional metamorphism of the highest grade (approximately synonymous with granulite).

leucocratic - Light-coloured; applied to light-coloured igneous rocks that are relatively poor in mafic minerals.

metasomatism - The process of practically simultaneous capillary solution and deposition by which a new mineral of partly or wholly different chemical composition may grow in the body of an old mineral or mineral aggregate.

miarolitic - A term applied to small irregular cavities in igneous rocks, especially granites, into which small crystals of the rock-form minerals protrude.

migmatite - A composite rock composed of igneous or igneous-appearing and/or metamorphic materials, which are generally distinguishable megascopically.

paleo- - A prefix denoting the attribute of great age or involving ancient conditions.

pegmatite - An exceptionally coarse-grained igneous rock, with interlocking crystals, usually found as irregular dikes, lenses or veins, especially at the margins of batholiths. They represent the last and most hydrous portion of a magma to crystallize and hence contain high concentrations of minerals present only in trace amounts in granitic rocks.

peralkaline - Said of an igneous rock in which the molecular proportion of aluminum oxide is less than that of sodium and potassium oxides combined.

phenocrysts - A relatively large, conspicuous crystal in a porphyritic rock.

pneumatolysis - Alteration of a rock or crystallization of minerals by gaseous emanations derived from solidifying magma.

polymictic/monomictic - Said of clastic sedimentary rocks composed of several/a single, respectively, mineral species.

porphyry - An igneous rock of any composition that contains conspicuous (large) crystals in a fine-grained groundmass.

pyroclastic - Pertaining to clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent.

seriate - Said of the texture of an igneous rock, typically porphyritic, in which the sizes of the grains vary gradually or in a continuous series.

skarn - A rock of complex mineralogical composition, formed by contact metamorphism and metasomatism of carbonate rocks.

stock - An igneous intrusion that is less than 100 square kilometres is surface exposure.

strata-bound - Said of a mineral deposit confined to a single stratigraphic unit.

subophitic - Said of the texture of an igneous rock in which the feldspar crystals are approximately the same size as the pyroxene and are only partially included by them.

supergene - Said of a mineral deposit or enrichment formed near the surface, commonly by descending solutions.

transgressive - Sediments deposited during the advance or encroachment of water over a land area or during the subsidence of the land.